Top-philic ALPs in the elusive mass window

Ken Mimasu

University of Southampton

[S. Blasi, F. Maltoni, A. Mariotti, KM, D. Pagani, S. Tentori; JHEP 06 (2024) 077]

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Science and Technology Facilities Council

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Axion-like particles

Axions: originally motivated by strong CP problem

$$\mathscr{L} \supset \frac{a}{f_a} G_A^{\mu\nu} \tilde{G}^A_{\mu\nu} \quad \Rightarrow \quad m_a f_a = \text{ constant}$$

ALPs: model of light, singlet pseudoscalar, a

- Generic, independent interactions

$$\{m_a, f_a\} \quad \text{independent}$$

- SM singlet

⇒ *Interactions described by EFT starting at dimension-5,* $O(1/f_a)$

- Pseudo Nambu-Goldstone boson

⇒ *light particle with shift-symmetric interactions*

$$a(x) \to a(x) + c \quad \Rightarrow \quad \mathscr{L} = \mathscr{L}\left[\partial^\mu a(x)\right]$$

- Appear in many well-motivated BSM scenarios

[Georgi, Kaplan & Randall; PLB 169 73 (1986)]

ALP interactions

explicit shift symmetry

$$\mathcal{L}^{(5)}_{ALP} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2} m_a^2\, a^2 + \frac{\partial^\mu a}{f_a} \sum_f \bar{\psi}_f \, \mathbf{c}_f \, \gamma_\mu \psi_f + c_H \frac{\partial^\mu a}{f_a} H^\dagger i \overleftrightarrow{D}_\mu H$$

$$+ c_{GG}\frac{\alpha_S}{4\pi}\frac{a}{f_a} G^{\mu\nu}_A \tilde{G}^A_{\mu\nu} + c_{WW}\frac{\alpha_2}{4\pi}\frac{a}{f_a} W^{\mu\nu}_I \tilde{W}^I_{\mu\nu} + c_{BB}\frac{\alpha_Y}{4\pi}\frac{a}{f_a} B^{\mu\nu}_I \tilde{B}_{\mu\nu}$$

shift symmetry breaking

Anomaly induced, ‘hidden’ shift symmetry

f: 5 fermonic SM representations $\{Q, L, u, d, e\}$

- $\mathbf{c}_f$ are matrices in flavor space

Not all operators independent: $\{c_H, [c_f]_{ij}\}$

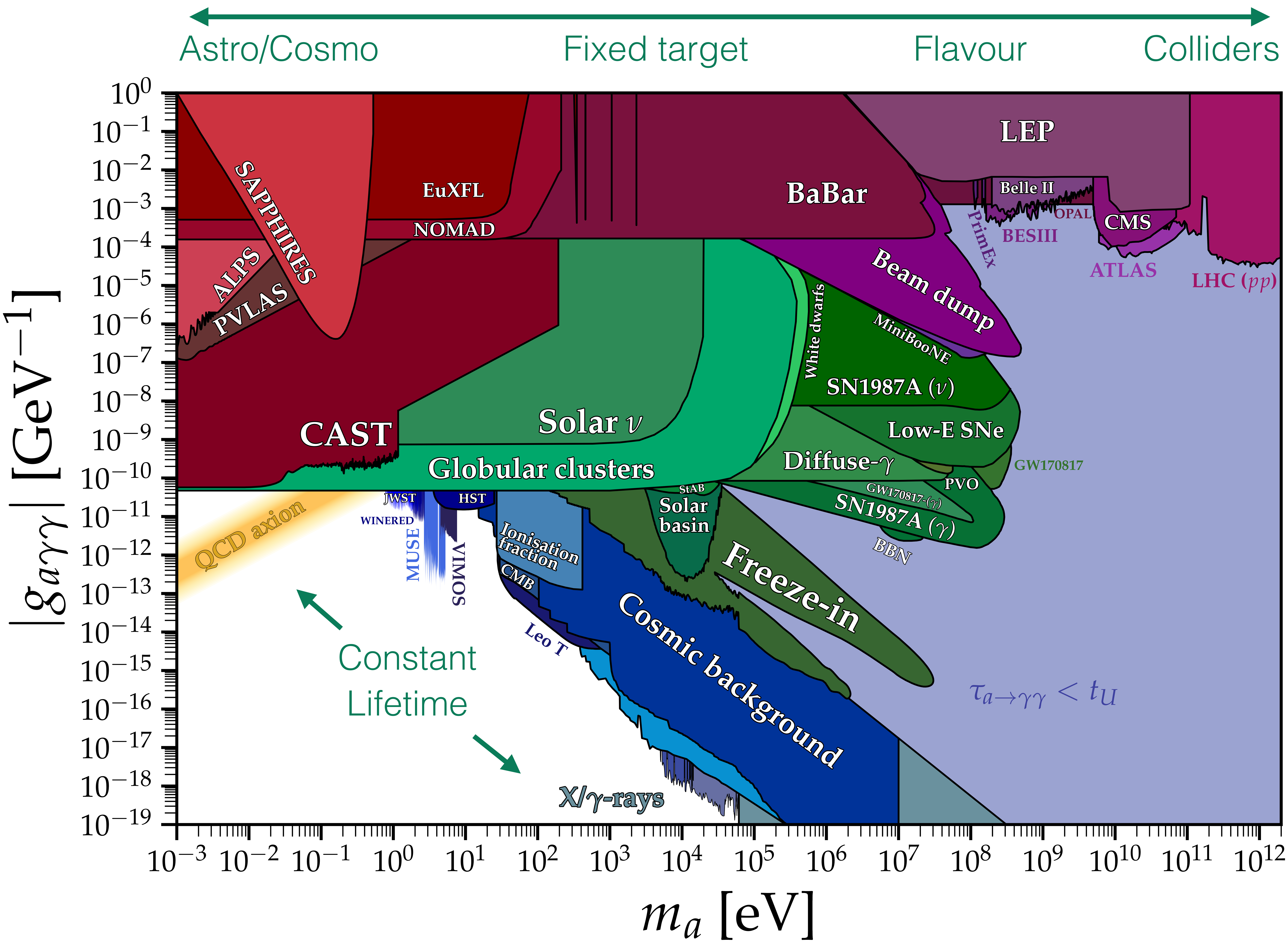
[Bauer, Neubert & Thamm; JHEP 12 (2017) 044]

Only one operator at dimension-6:

$$\mathcal{L}^{(6)}_{ALP} = \frac{c^{(6)}_{aH}}{f_a^2}(H^\dagger H)\, \partial^\mu a \partial_\mu a$$

[Grojean, Kley & Yao; JHEP 11 (2023) 196]

[O' Hare; https://cajohare.github.io/AxionLimits]



Top philic ALP

Consider an ALP that preferentially couples to the top quark

- e.g. t_R mixing mixing with new sector

$$\mathscr{L}^{(5)}_{top} = c_t \frac{\partial^\mu a}{f_a} \bar{t}_R \, \gamma_\mu \, t_R \,, \qquad c_t = \left[\mathbf{c}_u\right]_{33}$$

- Consistent with Minimal Flavor Violation

Recent works:

[Esser et al.; JHEP 09 (2023) 063]

[Biekötter et al.; JHEP 09 (2023) 120]

[Rygaard et al.; JHEP 10 (2023) 138]

[Bruggisser et al.; JHEP 01 (2024) 092]

[Hosseini et al; PRD 110 (2024) 5, 055026]

[Phan & Westhoff; JHEP 05 (2024) 075]

[Anuar et al.; 2404.19014]

Equivalent basis: $t_R \to t_R \, e^{-ic_t \frac{a}{f_a}}$

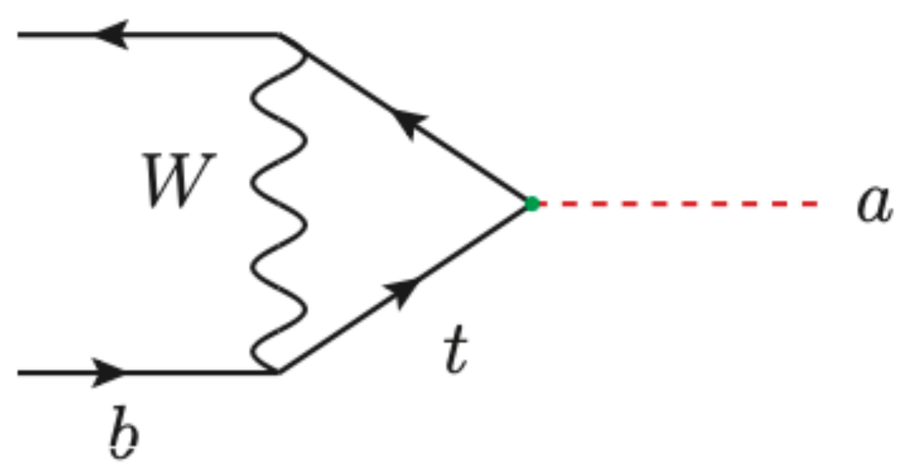
Derivative		Non-derivative (Yukawa-like)
$c_t \frac{\partial^\mu a}{f_a} \bar{t}_R \, \gamma_\mu \, t_R$	$\Leftrightarrow$	$c_t \frac{a}{f_a} \left(-i m_t \bar{t} \gamma_5 t + \frac{\alpha_S}{8\pi} G\tilde{G} + \frac{\alpha_Y}{3\pi} B\tilde{B} \right)$

Top-philic ALP ≠ top-philic pseudo scalar!

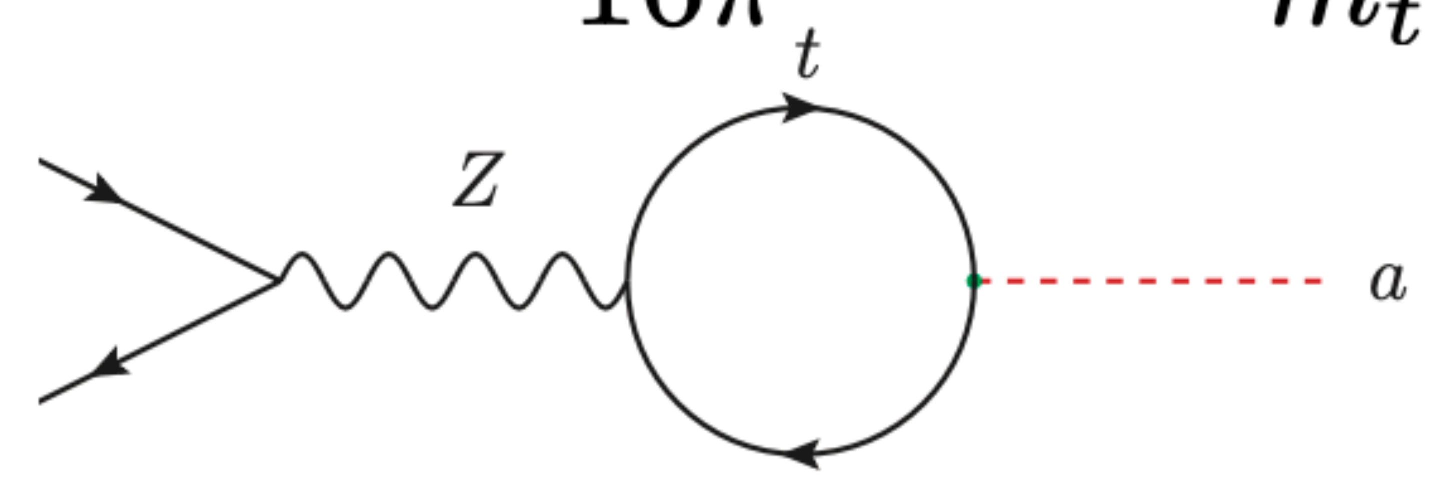
Top philic ALP couplings

Top coupling induces light fermion couplings, $c_{f \neq t}$

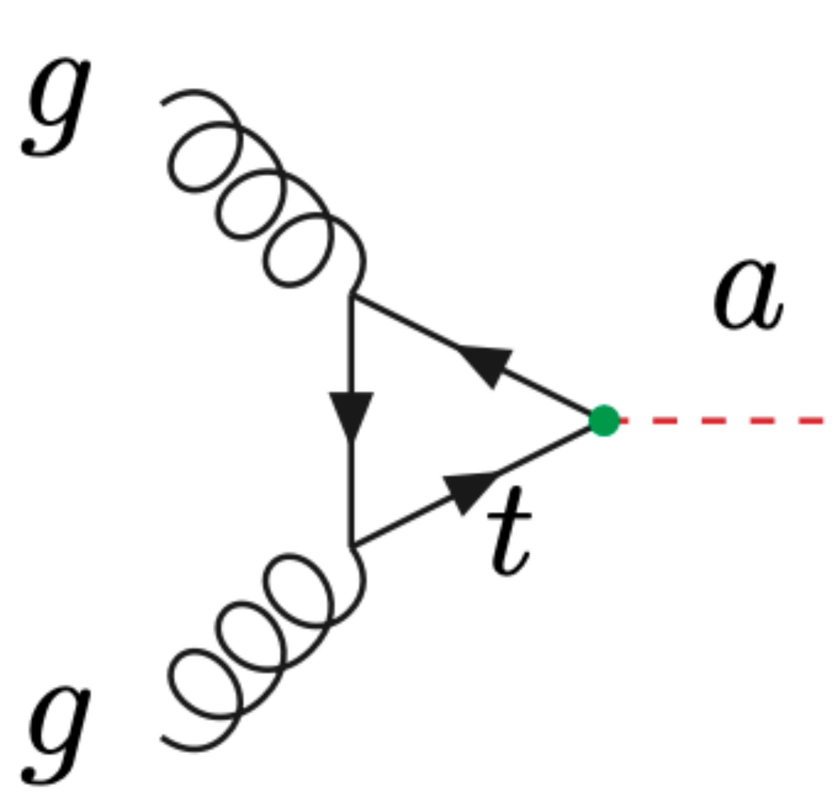
$$c_b \simeq 5 c_t \frac{y_t^2}{16\pi^2} \log \frac{\Lambda}{m_t}$$



$$c_f \simeq -12 c_t \frac{y_t^2}{16\pi^2} T_3^f \log \frac{\Lambda}{m_t}$$



Effective vertices between ALP & gauge bosons

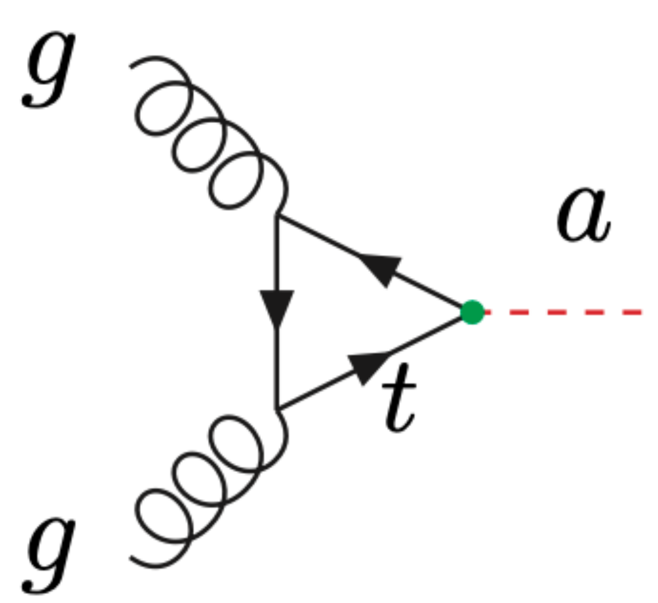


$+\gamma\gamma, Z\gamma, WW, ZZ$

[Neubert et al; JHEP 12 (2017) 044]
[Bonilla et al.; JHEP 11 (2021) 168]

Elusive gauge couplings

Induced $a \to gg$ amplitude (different from pseudoscalar)



$$\mathcal{A}^{\mu\nu}\left[a(k) \to g_a(p)\, g_b(q)\right] = i\frac{\alpha_S}{\pi}\frac{c_t}{f_a}\delta_{ab}p_\alpha q_\beta\,\epsilon^{\mu\nu\alpha\beta}\left[1 + 2m_t^2 C_0(p, q; m_t^2)\right]$$

$$k^2 \sim p^2 \sim q^2 \ll m_t^2 \quad \Rightarrow \quad \mathcal{A}^{\mu\nu} \to 0$$

Effective $aG\tilde{G}$ contact interaction

On-shell $(m_a \ll m_t)$ $\quad c_{GG}^{eff} \sim \frac{\alpha_S}{\pi}\frac{c_t}{f_a}\frac{m_a^2}{24m_t^2}$ $\qquad$ *Off-shell* $(k^2 \gg m_t^2)$ $\quad c_{GG}^{eff} \sim \frac{\alpha_S}{\pi}\frac{c_t}{f_a}$

Induced light fermion couplings can be relevant

$$c_{GG}^{eff} \sim \frac{\alpha_S}{\pi}\frac{c_t}{f_a}\left[\frac{m_a^2}{24m_t^2} + \frac{5}{2}\frac{y_t^2}{16\pi^2}\log\frac{\Lambda}{m_t}\right]$$

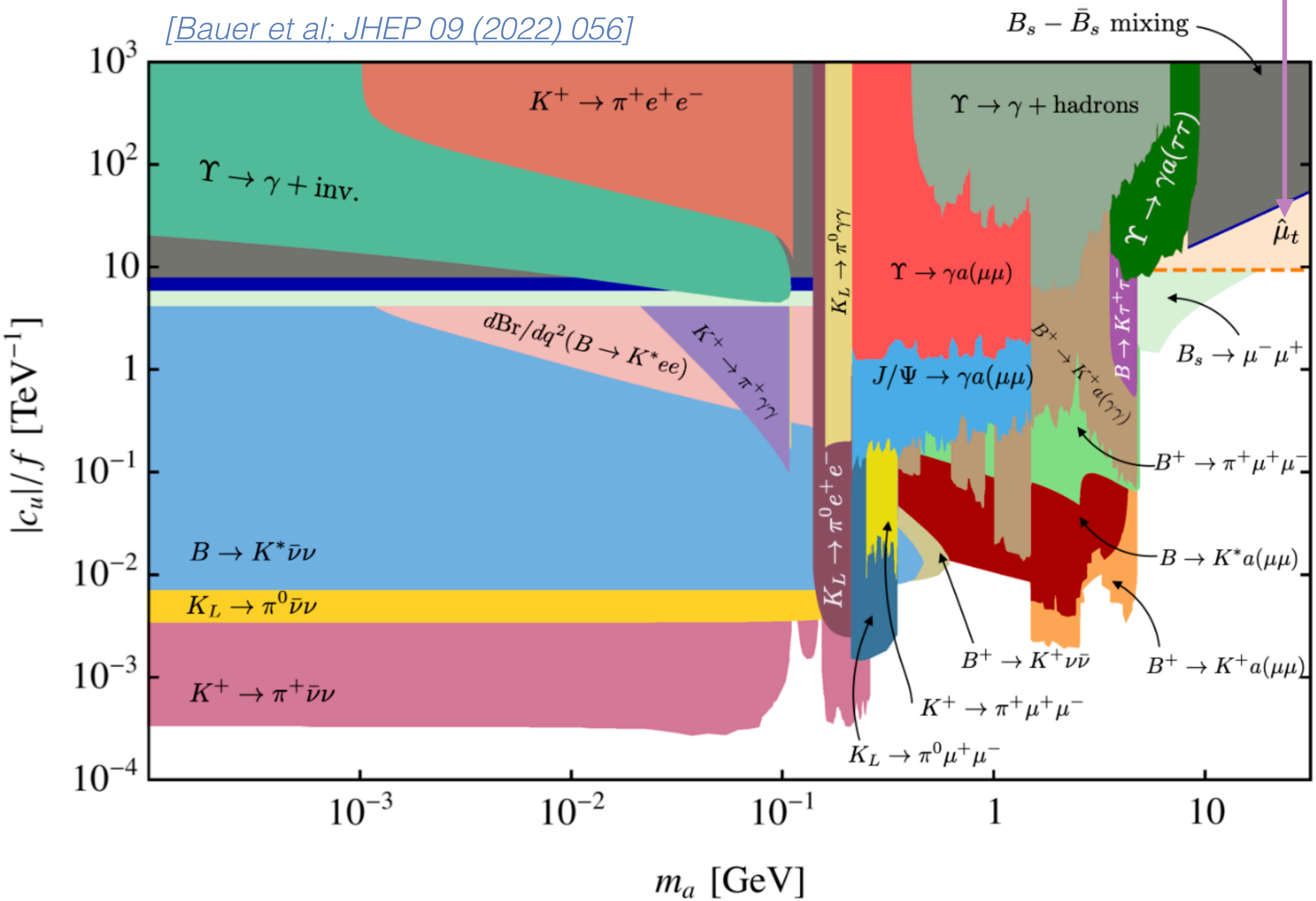
e.g. for ALP production & decay
(same for $a \to \gamma\gamma$)

Flavour probes

[Ebadi et al; PRD 100 (2019) 015016]

Top chromo-magnetic dipole bound

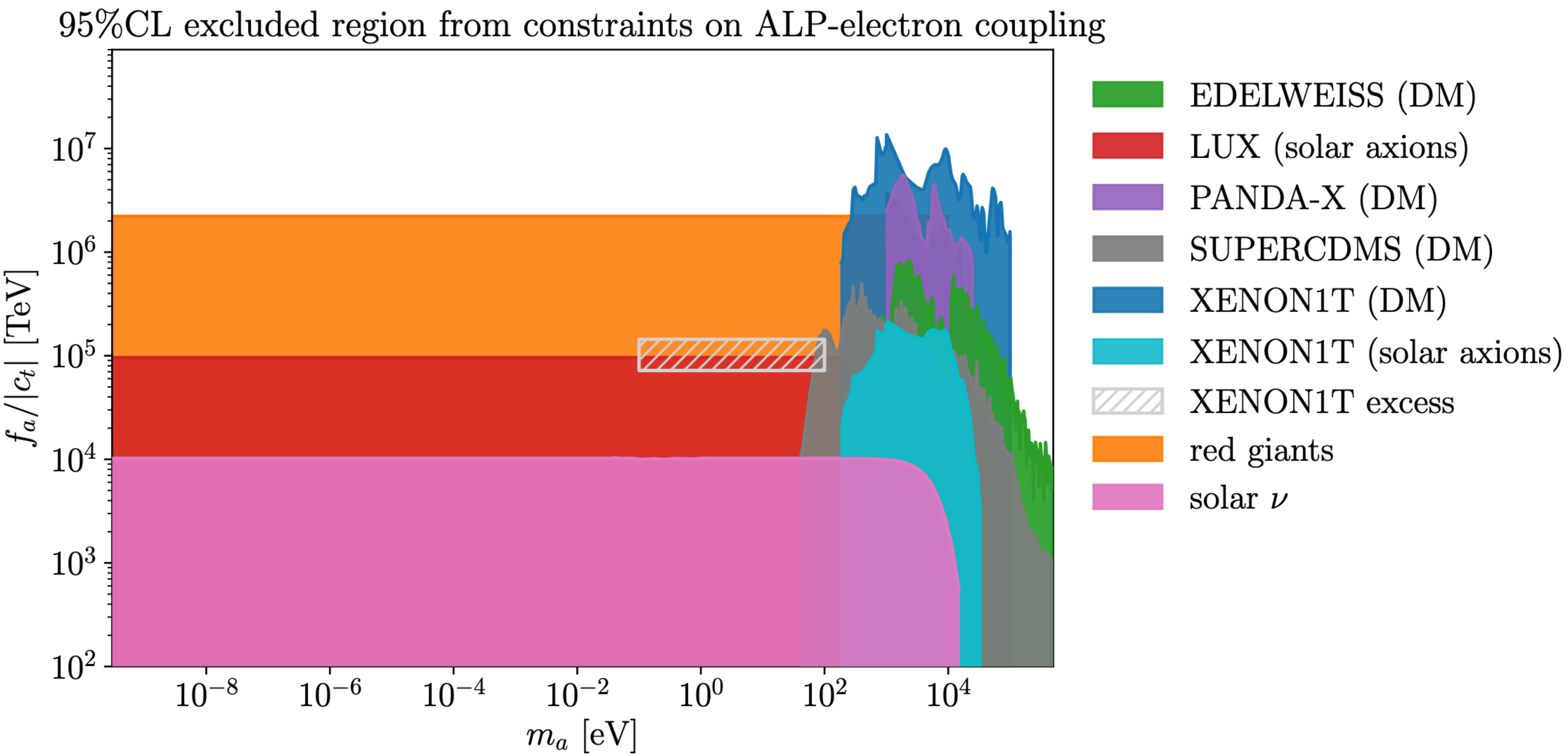
[Bauer et al; JHEP 09 (2022) 056]



[Bonilla et al; JHEP 11 (2021) 168]
[Chala et al.; EPJC 81 (2021) 181]

Stellar/DM bounds

Strong limits from RG-induced ALP-electron coupling



Elusive mass window

$$10 \lesssim m_a \lesssim 200\,\mathrm{GeV}$$

Strong bounds from astro/flavour below $m_a \sim$ few GeV

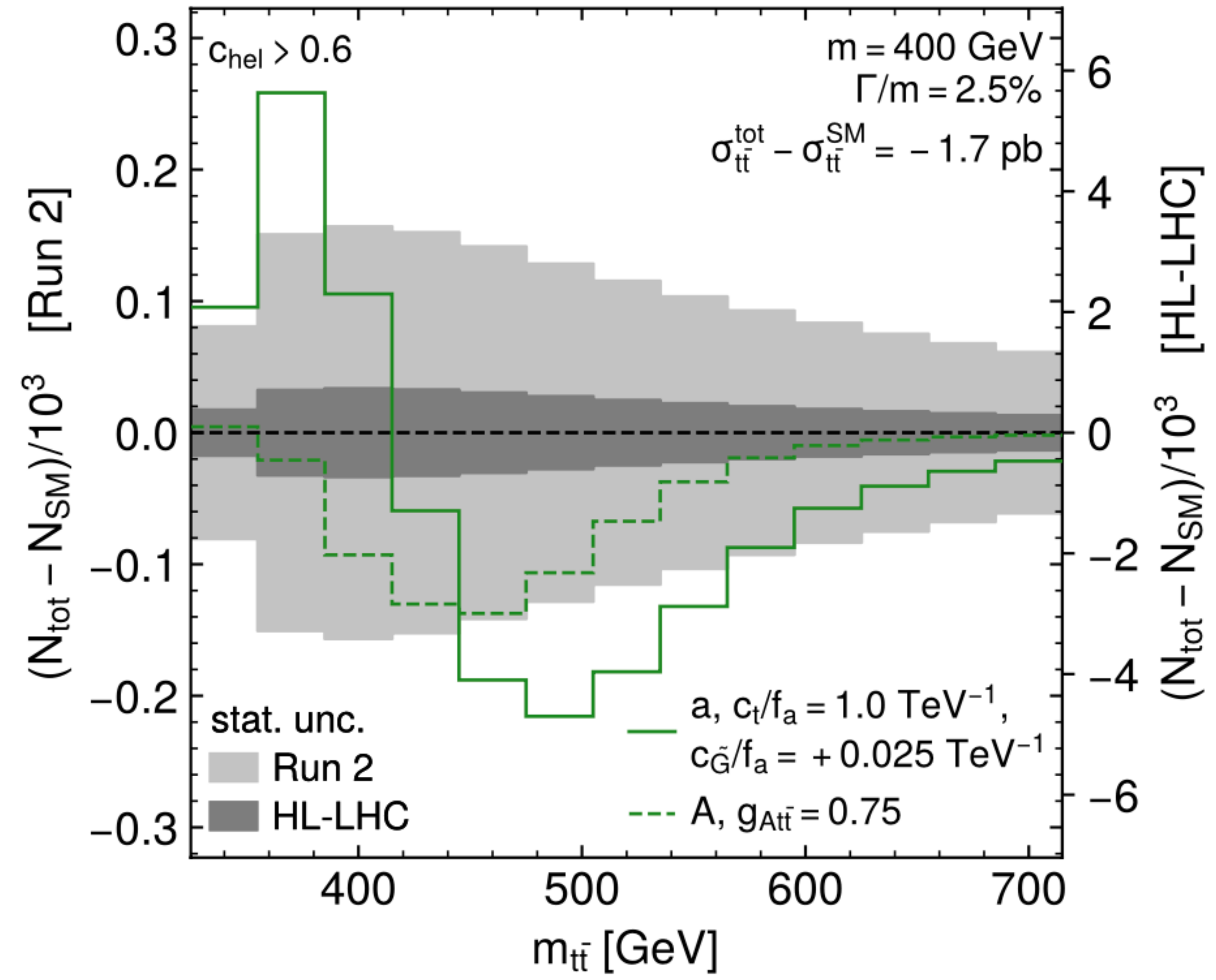
- ALP possibly long-lived

[Esser et al.; JHEP 09 (2023) 063]
[Bruggisser et al.; JHEP 01 (2024) 092]

Larger m_a means shift symmetry breaking effects $\propto m_a^2$

- Decays to gauge bosons unsuppressed

$m_a > 2m_t$, on-shell top decays $\Rightarrow t\bar{t}$ resonance searches



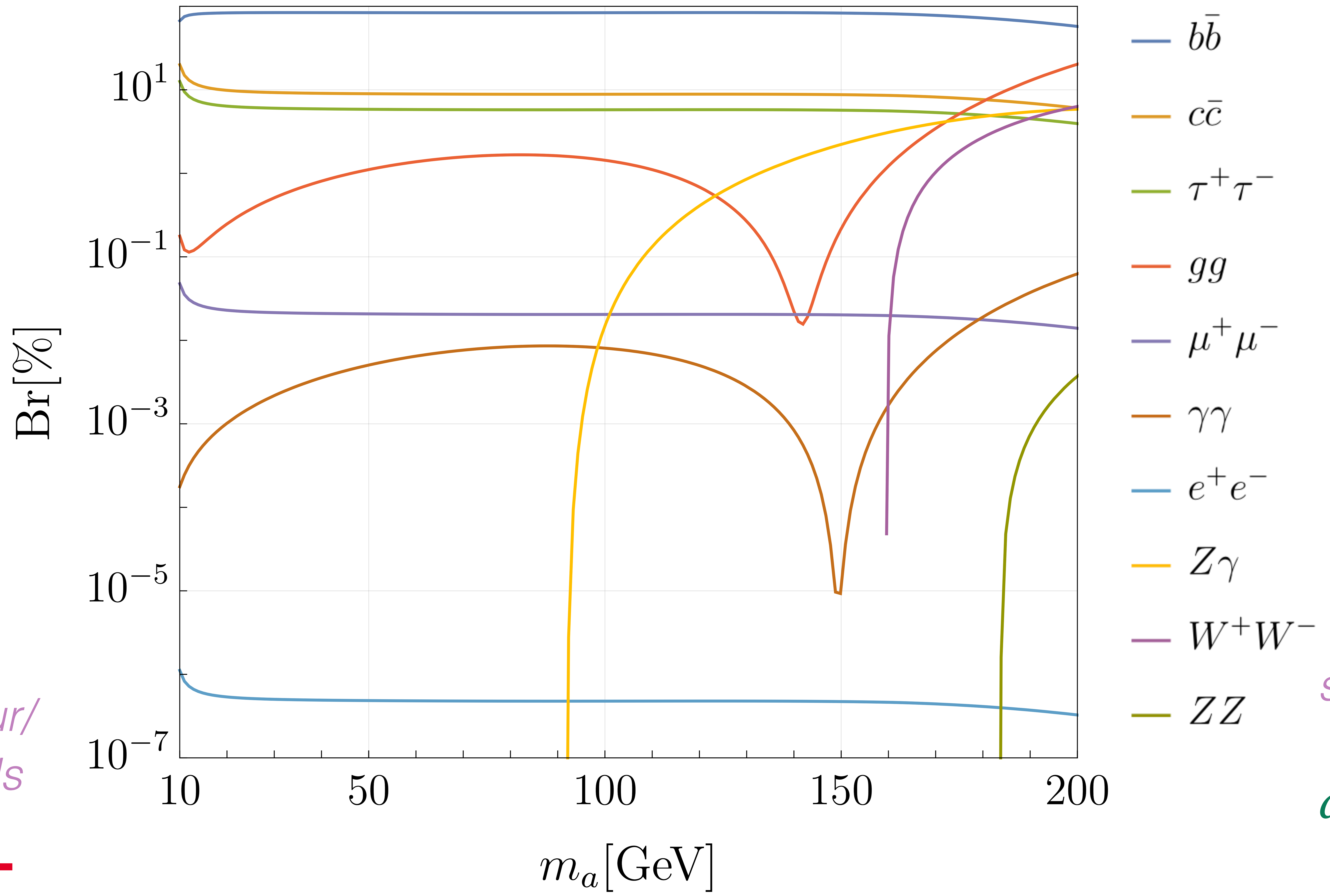
[Anuar et al.; 2404.19014]

See also Laurids Jeppe's poster

- Peak-dip structure from interference in $gg \to t\bar{t}$
- ALP differs from top-philic pseudo scalar

Branching ratios

dominant $b\bar{b}$ decays



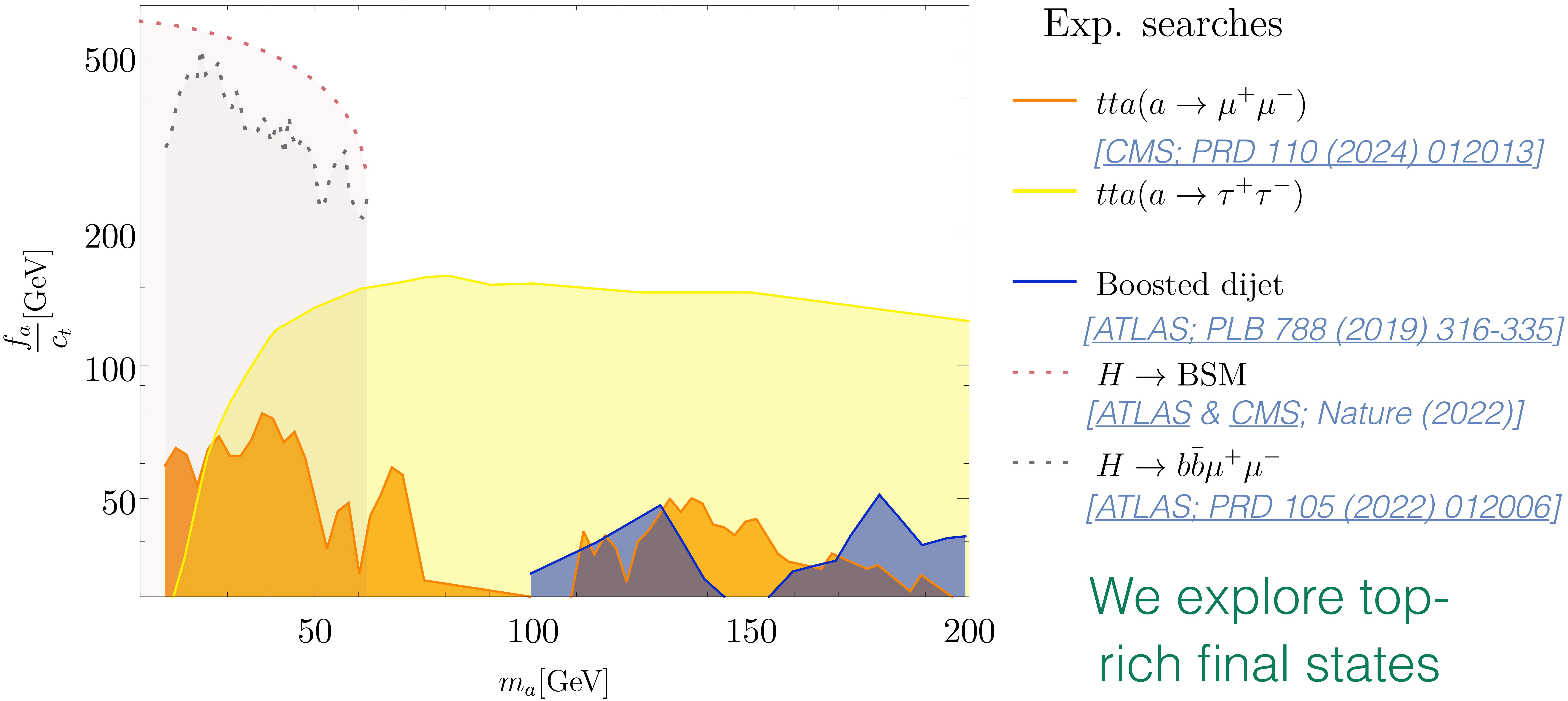
strong flavour/ astro bounds ←

shift-symmetry breaking: $a \to gg, \gamma\gamma, t\bar{t}$ →

Bounds in elusive window

Recast light scalar resonance searches

- $t\bar{t}a$ production, boosted dijet & $h \to aa^*$

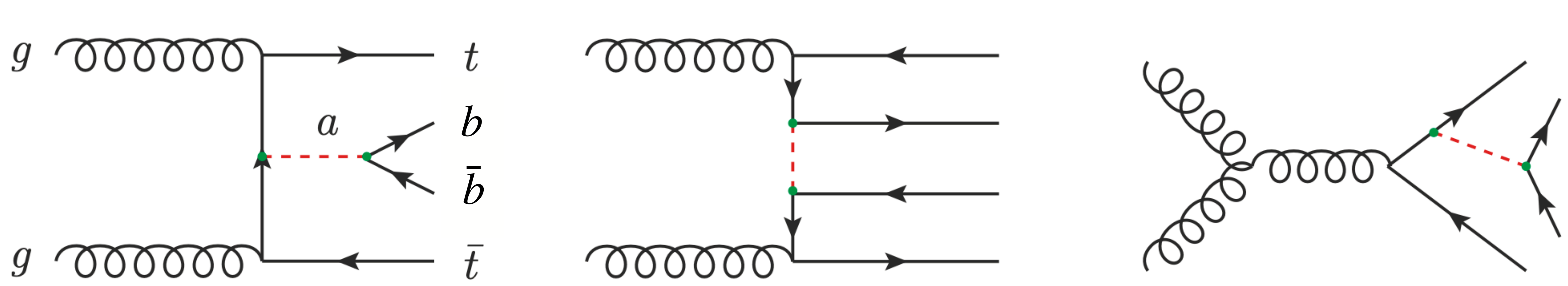


We explore top-rich final states

Resonant ALPs in $t\bar{t}b\bar{b}$

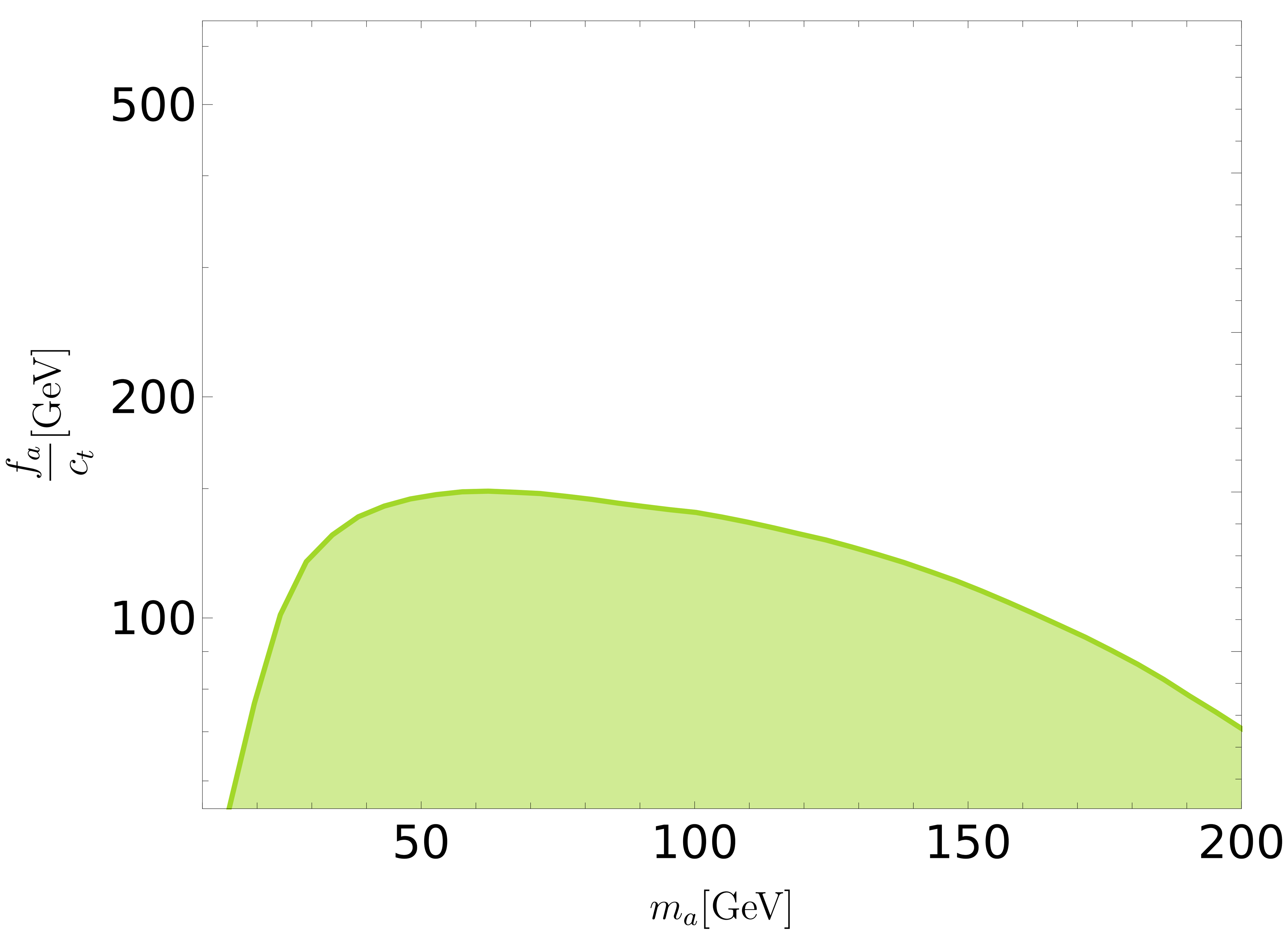
Top pair associated production into primary $b\bar{b}$ decay mode

- Constrain contribution to $t\bar{t}b\bar{b}$ signal strength measurements



Exp.	Channel	$\mu_{t\bar{t}b\bar{b}} \pm$ stat. $\pm$ syst.
CMS	dilepton	$1.36 \pm 0.10 \pm 0.34$
CMS	lepton+jets	$1.26 \pm 0.04 \pm 0.31$
ATLAS	dilepton ($e\mu$, 4b)	$1.75 \pm 0.05 \pm 0.56$
ATLAS	lepton+jets (4b)	$1.57 \pm 0.09 \pm 0.49$

[ATLAS; JHEP 04 (2019) 046]
[CMS; JHEP 07 (2020) 125]



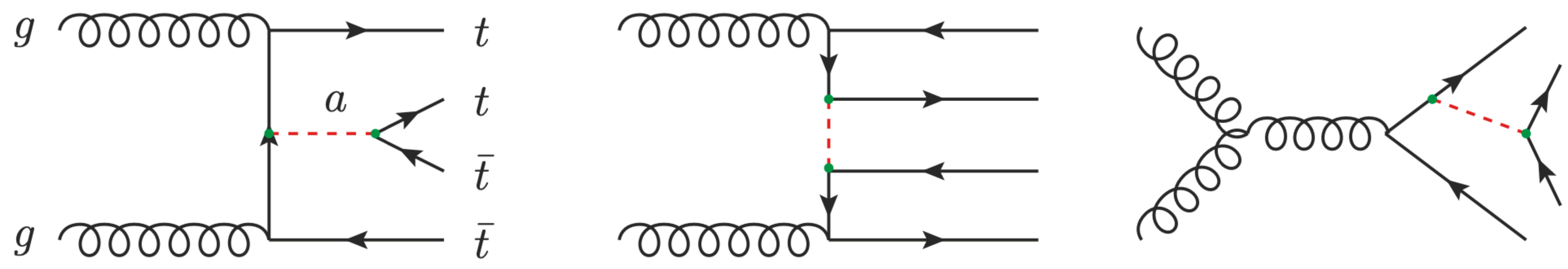
- Significant b-tagging and modelling systematics
- Resonant channels dominate
- Dedicated resonance search should be beneficial

Non-resonant ALPs in $t\bar{t}t\bar{t}$

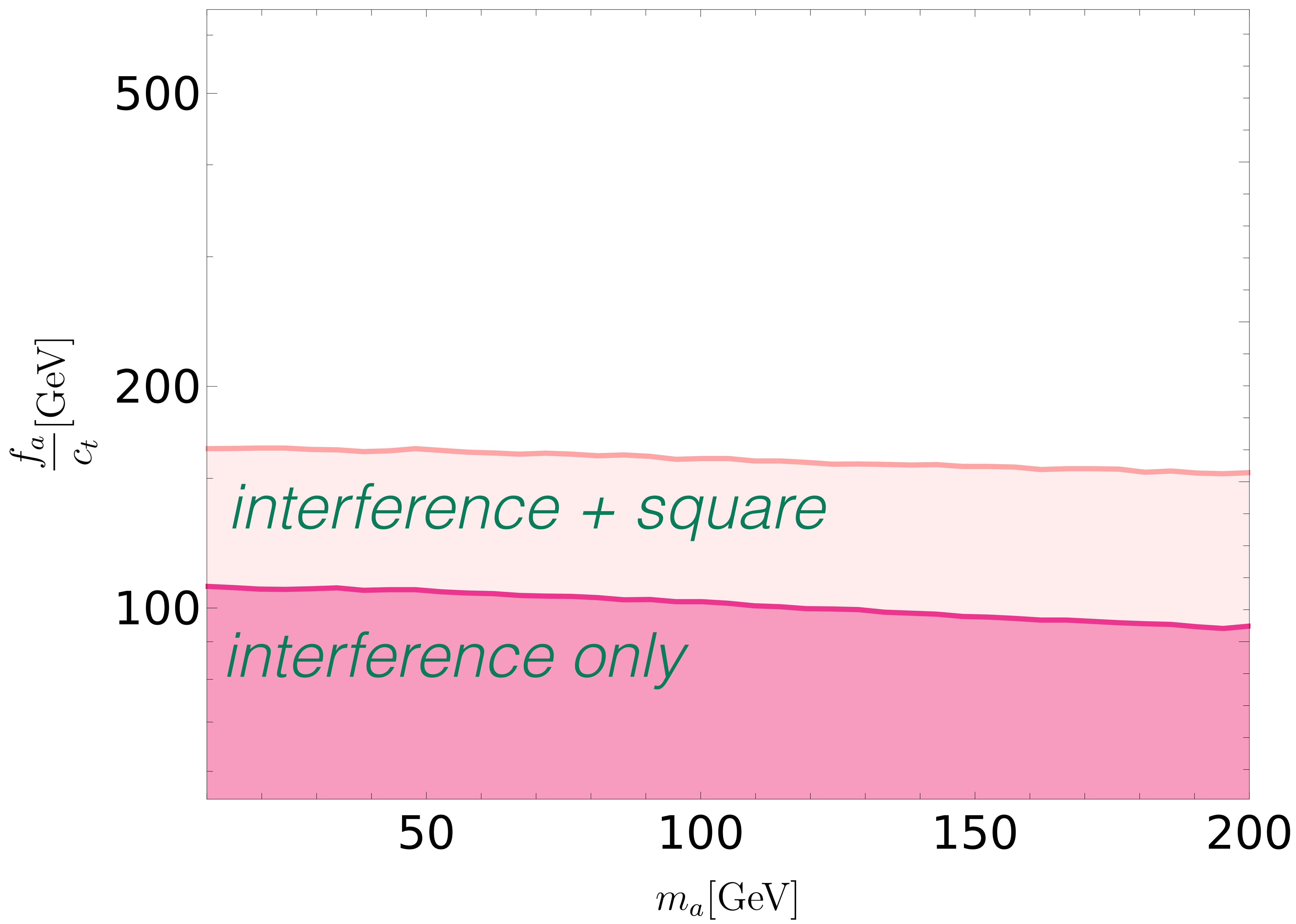
[ATLAS; EPJC 83 (2023) 496]
[CMS; PLB 847 (2023) 138290]
[CMS; PLB 844 (2023) 138076]
[ATLAS; JHEP 11 (2021) 118]

Purely non-resonant $(m_a < 2m_t)$

- Corrections to total four top cross section



Exp.	Channel	$\mu_{t\bar{t}t\bar{t}} \pm$ stat. $\pm$ syst.
ATLAS	SSDL+ML	$1.70 \pm 0.40^{+0.7}_{-0.4}$
ATLAS	OSDL+1L	$2.00 \pm 0.70^{+1.5}_{-1.0}$
CMS	SSDL+ML	$1.32 \pm 0.27^{+0.2}_{-0.23}$
CMS	OSDL+1L	$2.20 \pm 0.50 \pm 0.50$



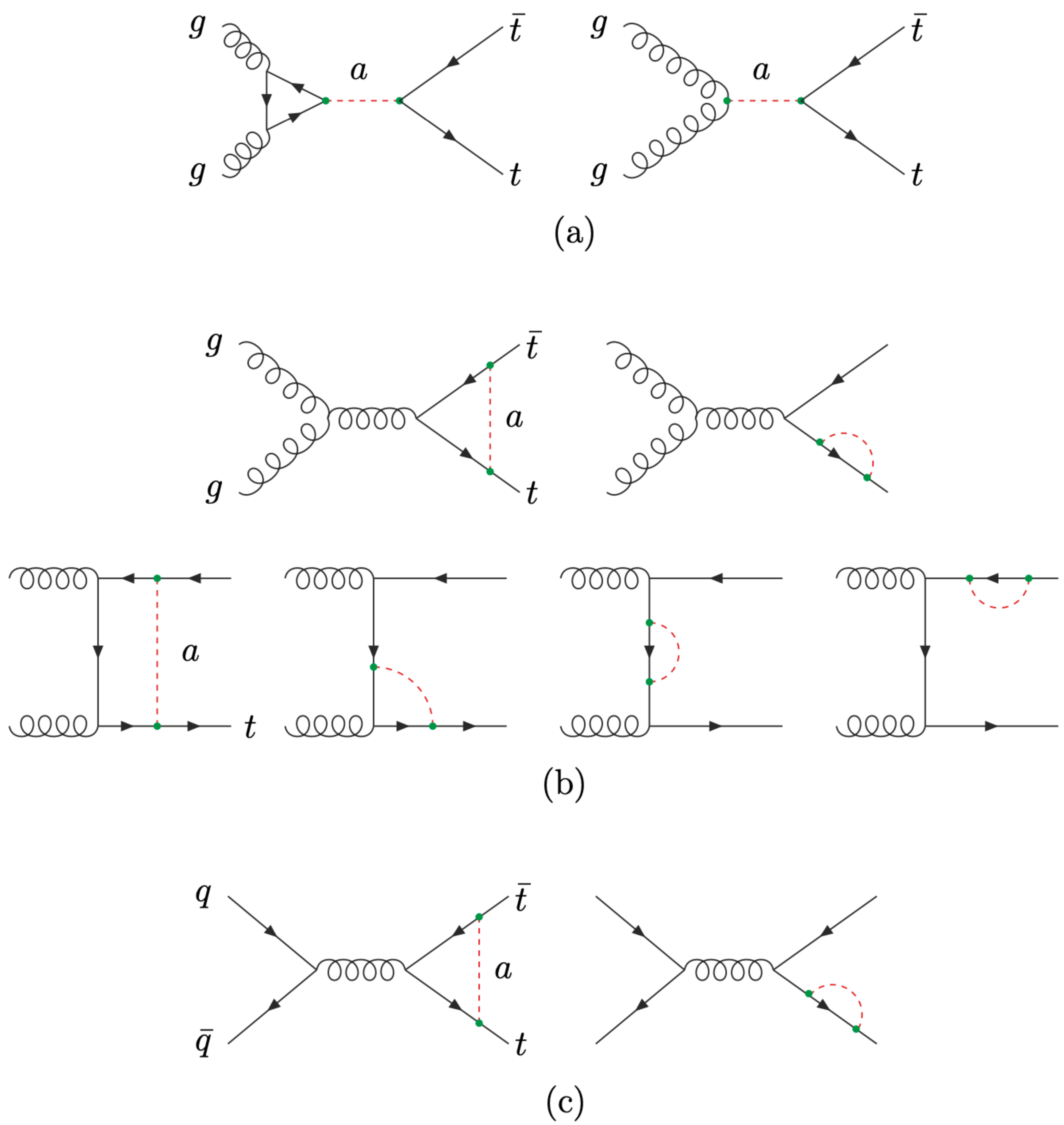
- Included mixed QCD/QED contributions
- Combined 4 recent $t\bar{t}t\bar{t}$ analyses
- Latest SM prediction
  [van Beekveld et al.; PRL 131 (2023) 21, 211901]
- Comparable contributions from:

  interference w/ SM $\propto c_t^2$

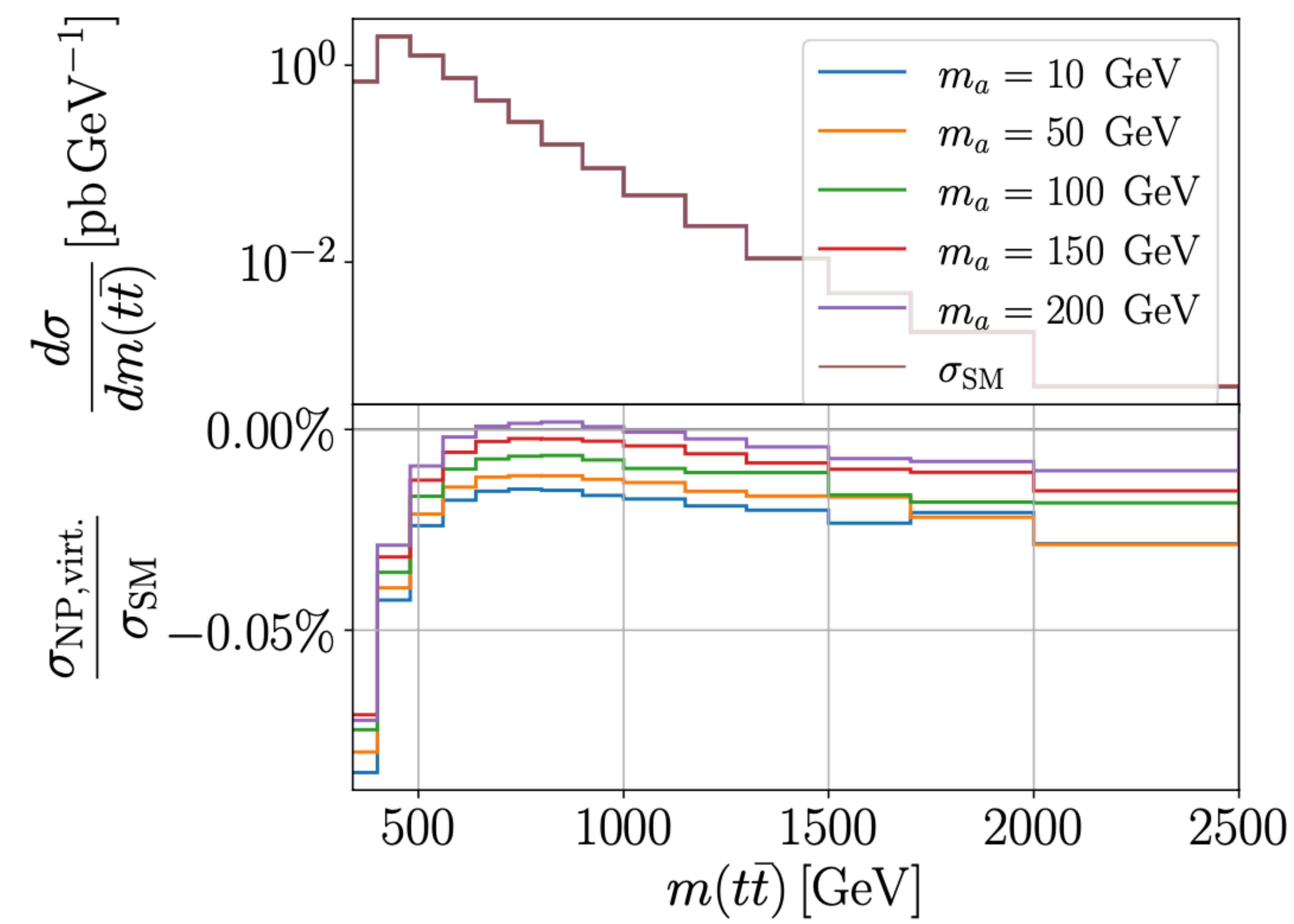
  ALP diagram squared $\propto c_t^4$

Indirect ALPs in $t\bar{t}$

Loop corrections to $t\bar{t}$ production: $\sigma = \sigma_{SM} + \sigma_{\text{virt.}} + \sigma_{\text{real}}$



(Diagrams in non-derivative basis)

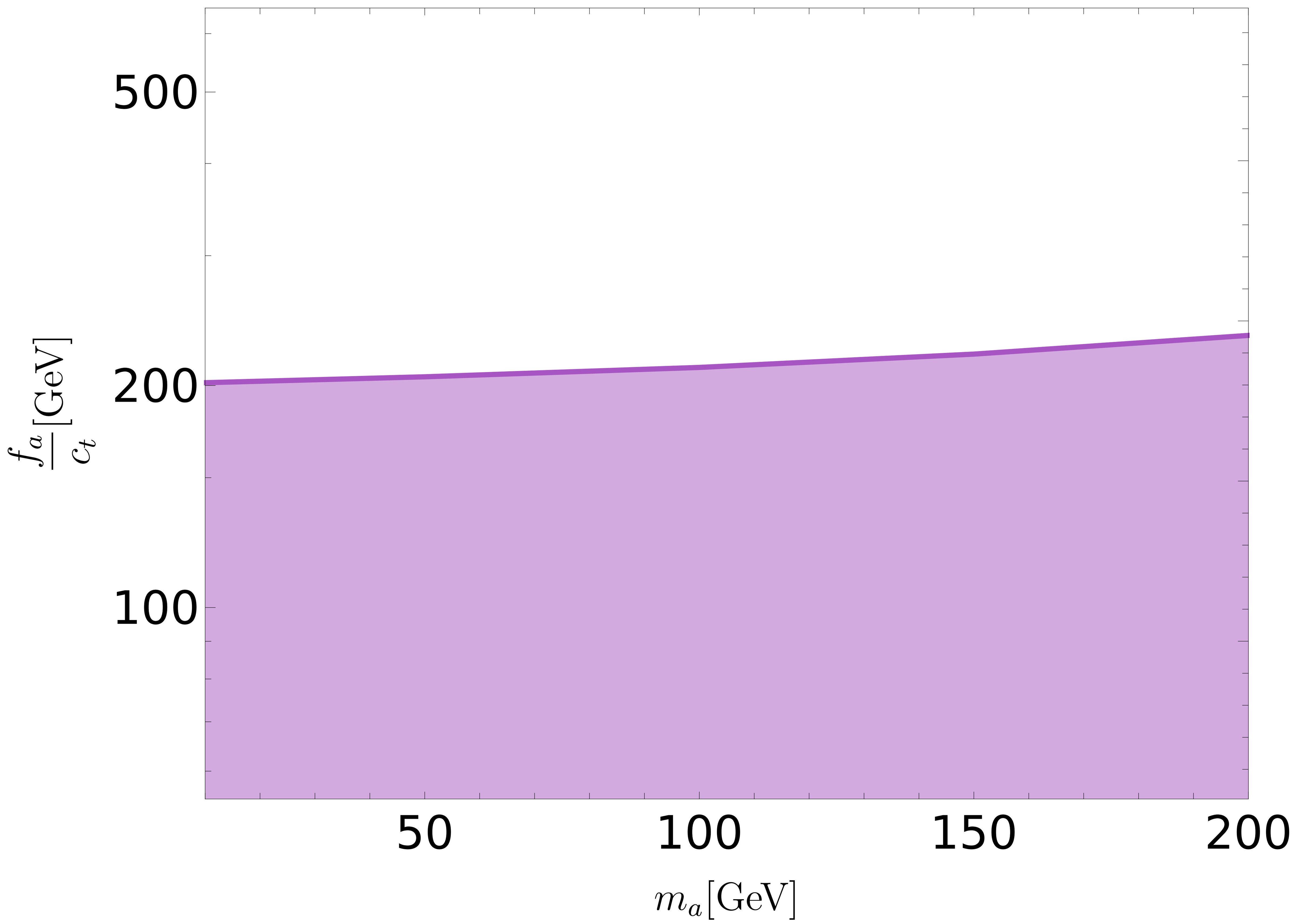


- Real corrections negligible
- $\sigma_{\text{virt.}} \sim c_t^2$ is interference w/ SM
- Large deviation near threshold

Indirect ALPs in $t\bar{t}$

Combined several $t\bar{t}$ measurements from LHC experiments

- From `fitmaker` database [Ellis, Madigan, KM, Sanz, You; JHEP 04 (2021) 279]
- Non-overlapping combination of $m_{t\bar{t}}$ & p_T distributions (see backup)
- Including correlations where available

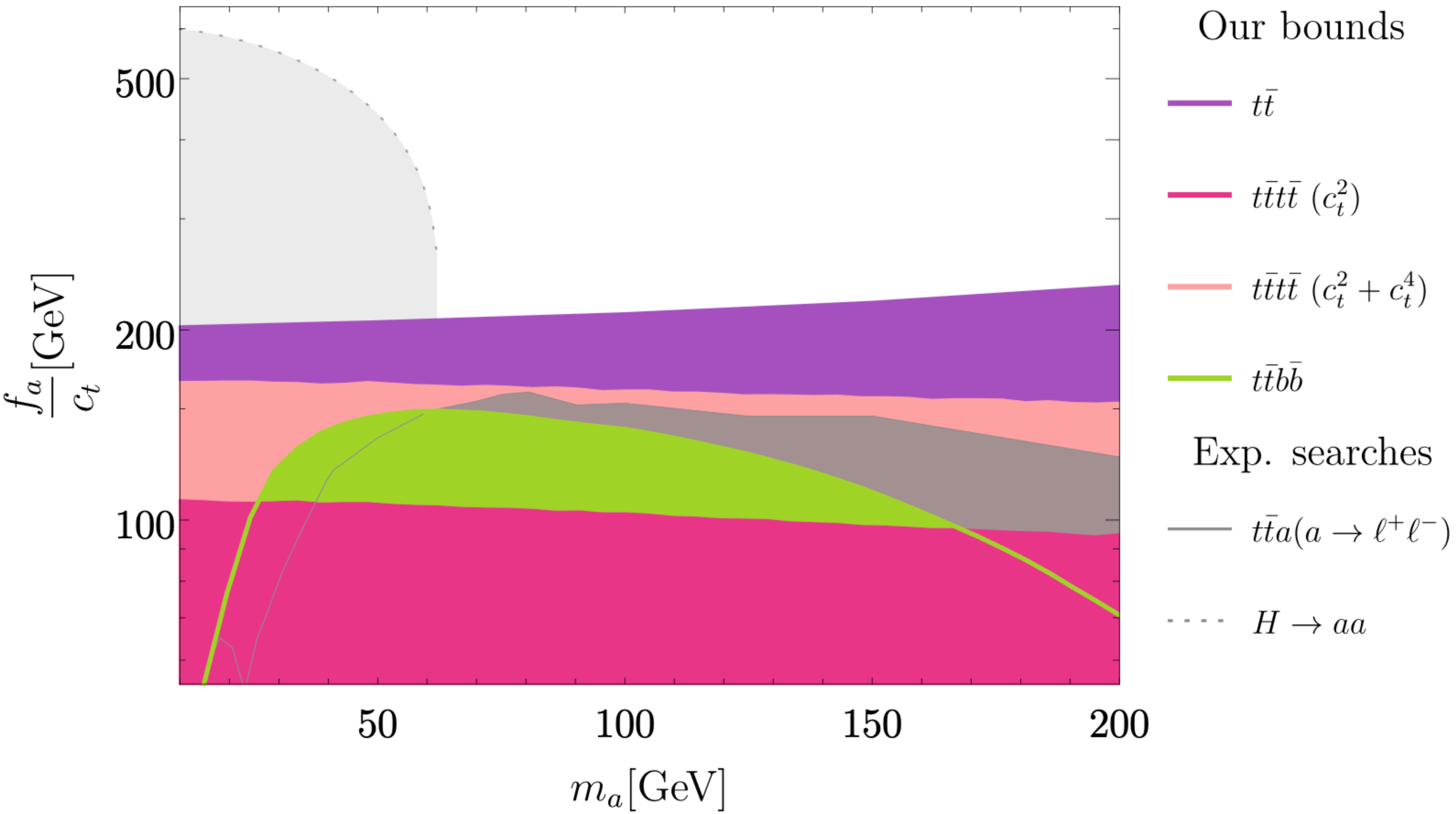


Bounds

m_a [GeV]	10	50	100	150	200
$\frac{f_a}{c_t}$ [GeV]	201	206	212	221	234

- Mild dependence on m_a
- Outperforms previous searches
- Better sensitivity than $t\bar{t}b\bar{b}$ & $t\bar{t}t\bar{t}$

Summary of top-rich bounds

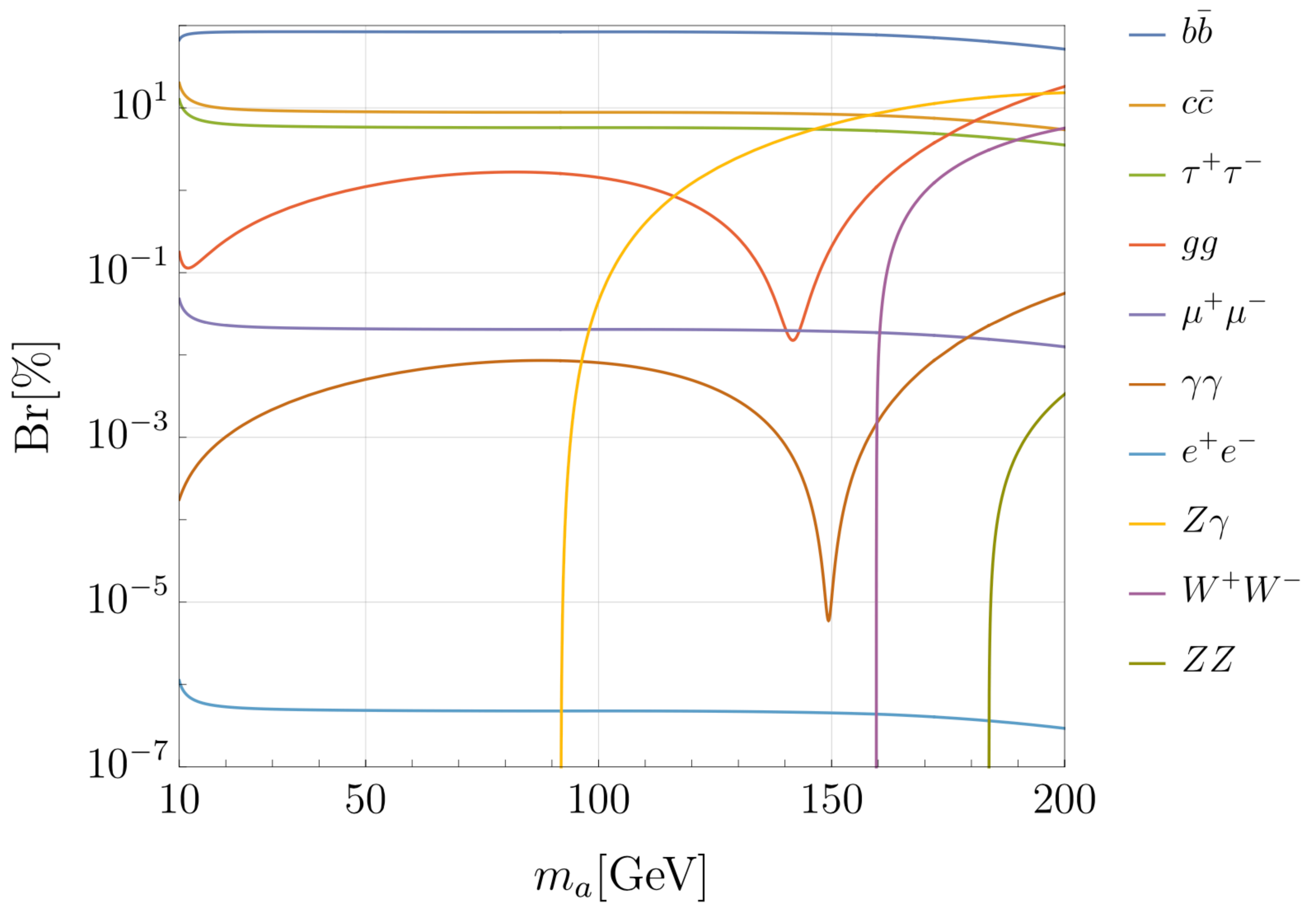


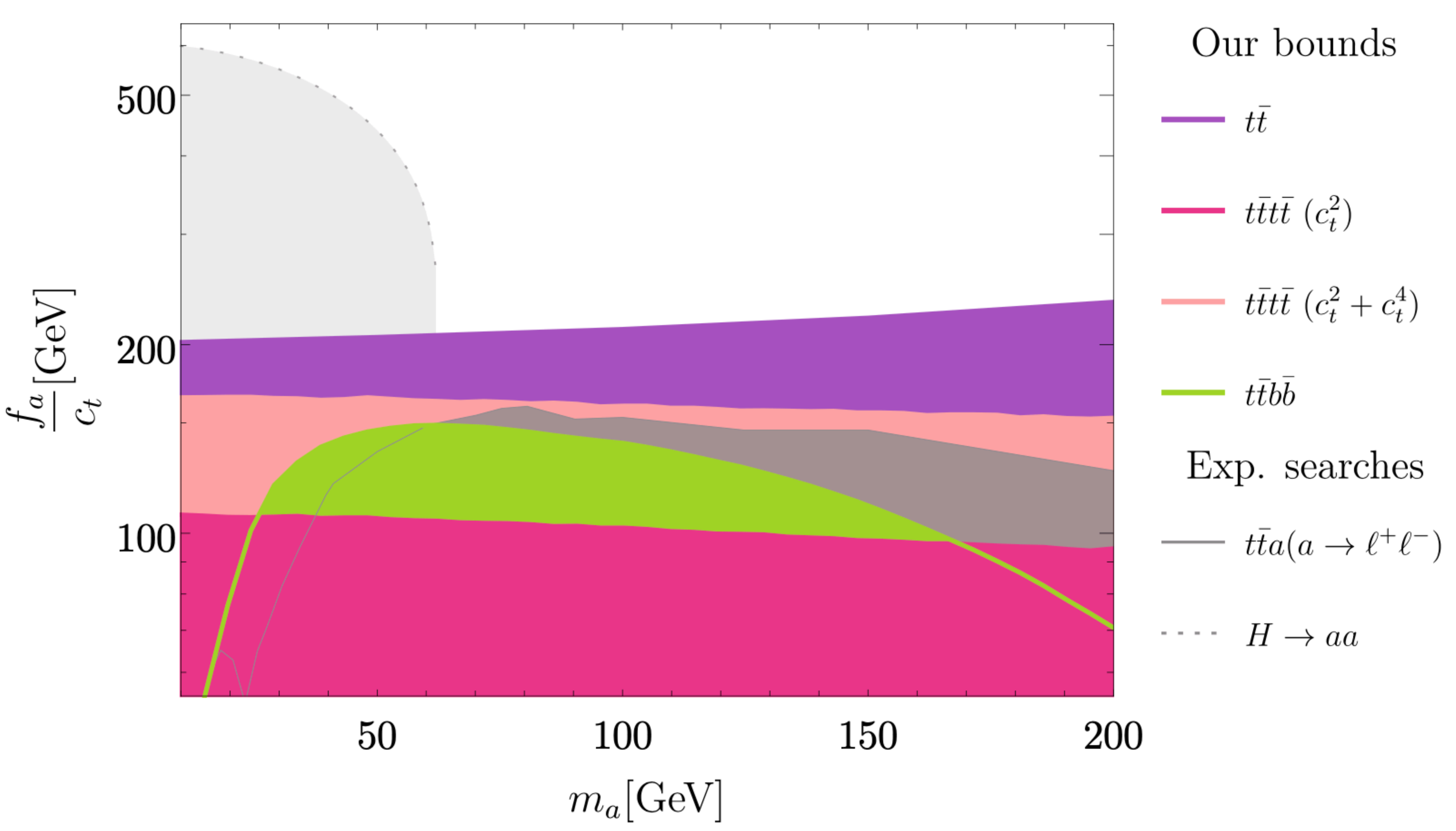
The elusive ALP

Top-philic ALP with $10 \lesssim m_a \lesssim 100\,\mathrm{GeV}$ remains elusive…

- Suppressed couplings to gauge bosons make for tough direct searches
- Exotic Higgs decay mode competitive but comes with caveat (see backup)
- Top-rich bounds constrain $f_a/c_t \sim 200\,\mathrm{GeV}$

EFT valid for strongly coupled scenario

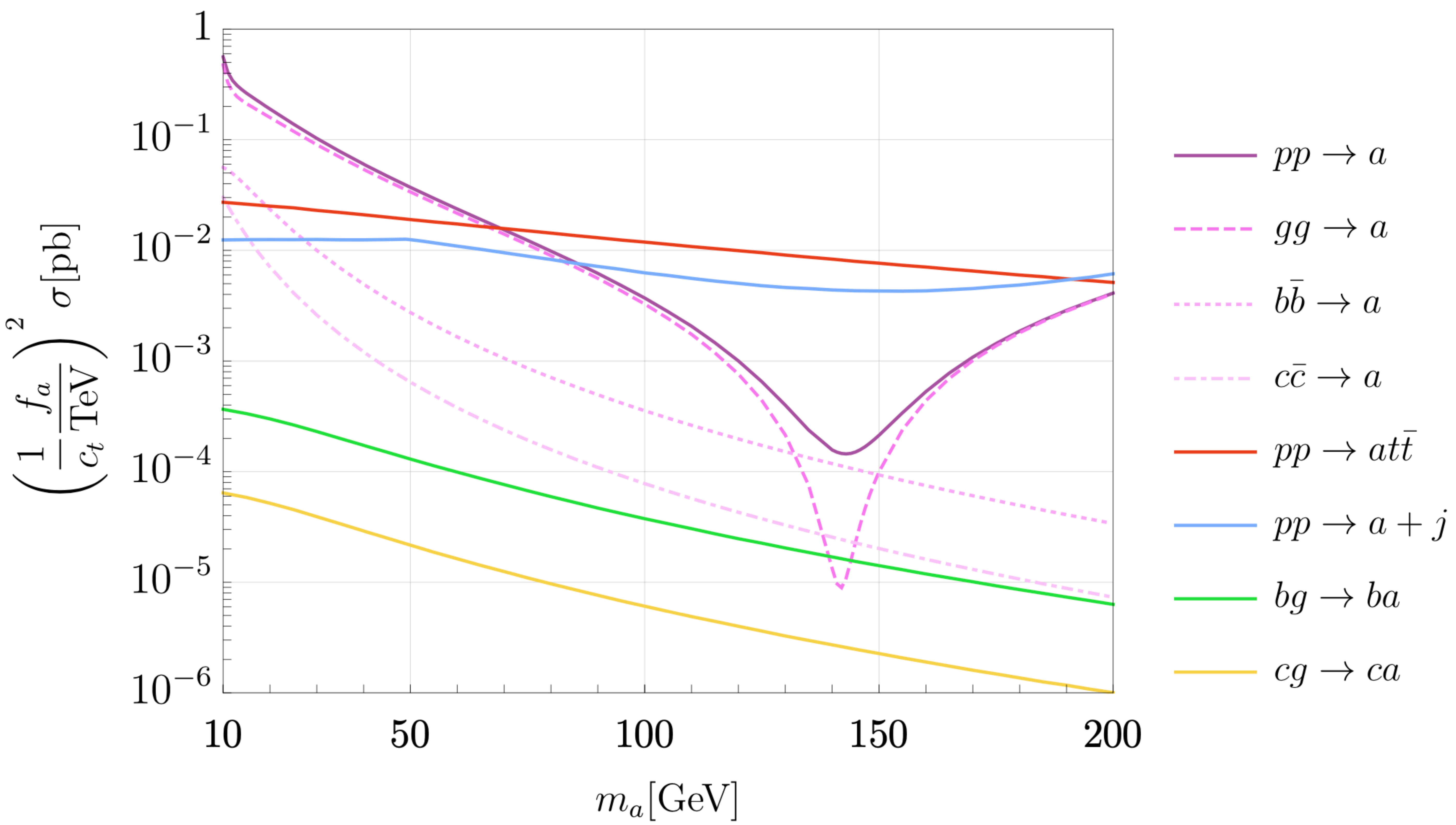


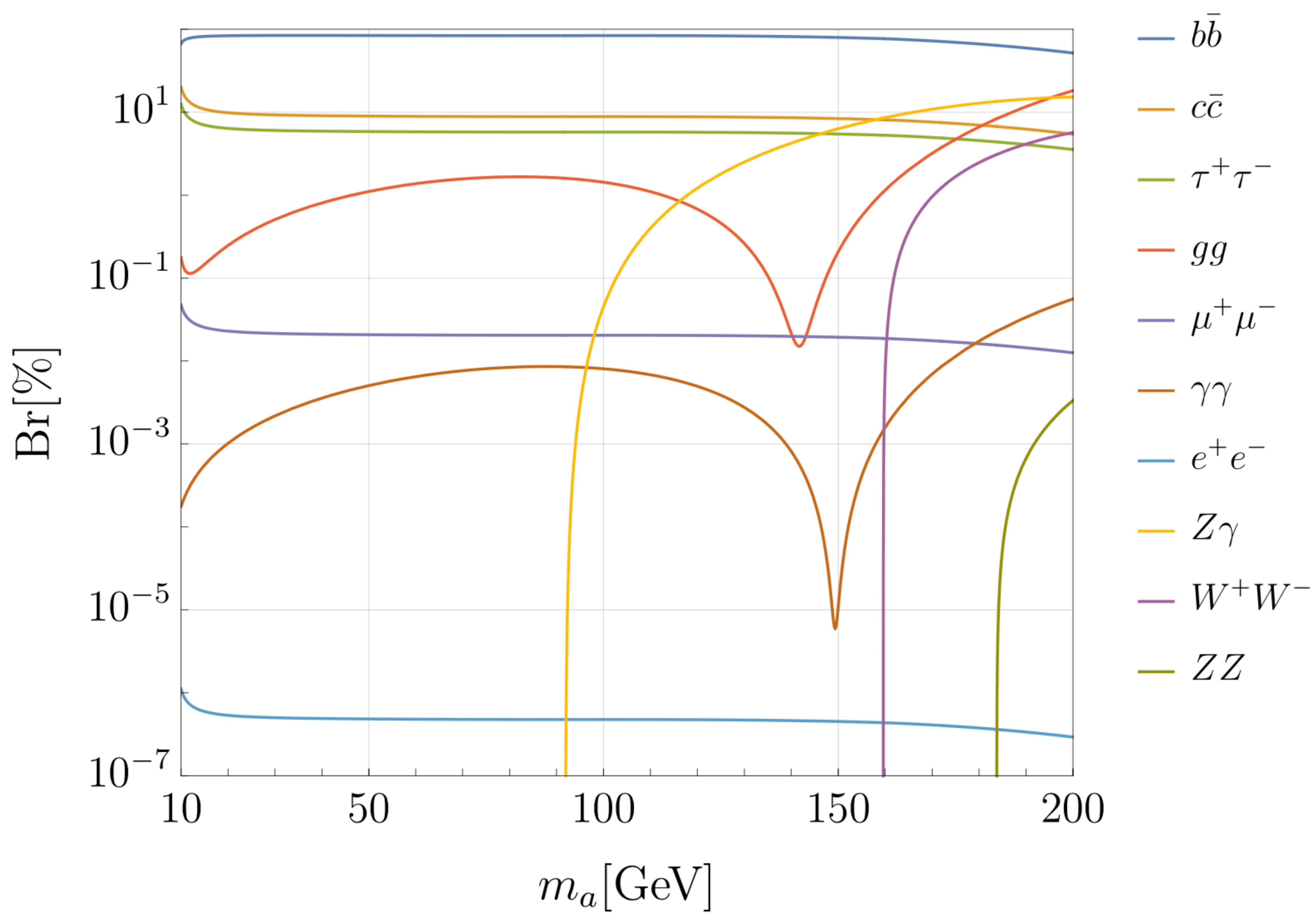


What next?

Dedicated resonance searches

- $m_a > 90\,\mathrm{GeV},\ a \to Z\gamma$
- $m_a > 160\,\mathrm{GeV},\ a \to W^+W^-$
- $t\bar{t}a$ production mode dominates at these masses
- Interesting top-rich signatures with small SM backgrounds
- Dedicated studies in progress… stay tuned!





Conclusions

$$10 \lesssim m_a \lesssim 200\,\mathrm{GeV}$$

Top philic ALP is an interesting yet elusive collider target

- Direct $gg \to a$ production mode suppressed & predominant $b\bar{b}$ decay
- Precision measurements of top-rich final states can be used as searches
- Best bounds come from $t\bar{t}$ differential distributions & $h \to \mathrm{BSM}$

Developed a dedicated UFO model for MC simulations

- Currently not public

[Maltoni et al; JHEP 09 (2024) 098]

Dedicated searches would be welcome

- Non-resonant, kinematic distributions in e.g. $t\bar{t}$ & $t\bar{t}t\bar{t}$
- Resonant: $t\bar{t}a$ production with decays to $b\bar{b}/Z\gamma/WW$

Not discussed today: top-philic ALP as DM mediator *[backup]*

Backup

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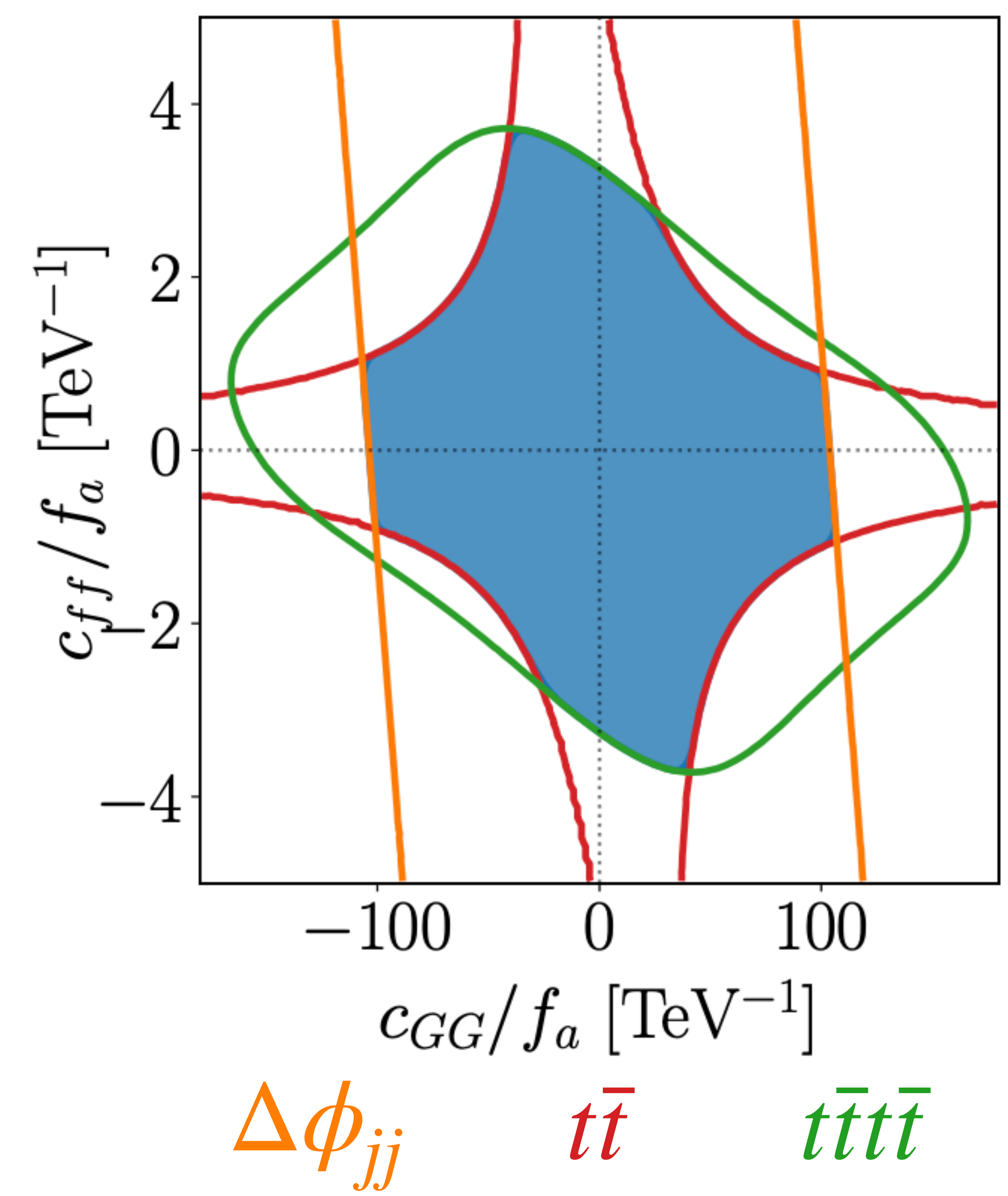
Global approach

Generic ALP should be studied from global perspective

- More than one coupling at a time ⇒ correlations
- Enable constraints on generic UV completions

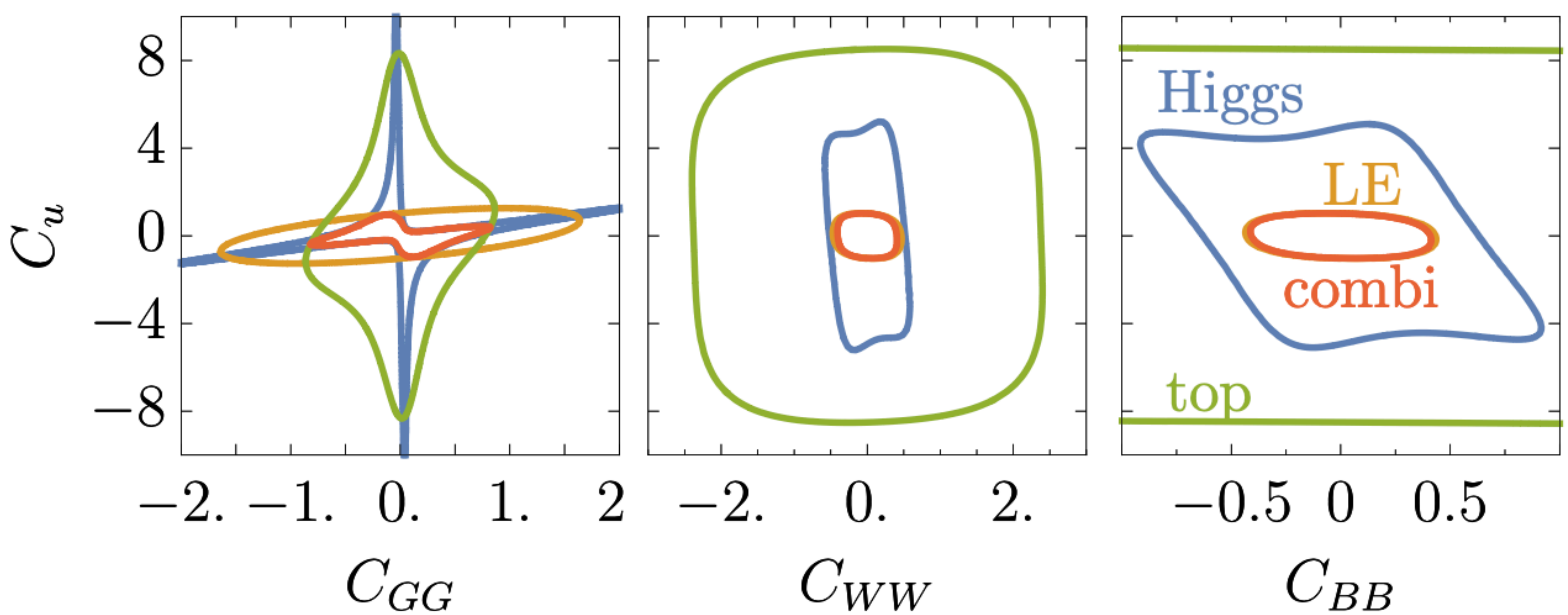
[Bruggisser et al; JHEP 01 (2024) 092]



ALP-SMEFT mixing:

[Biekötter et al; JHEP 09 (2023) 120]

$$\frac{\mathrm{d}}{\mathrm{d}\log\mu} C_i^{\mathrm{SMEFT}} - \gamma_{ji}^{\mathrm{SMEFT}} C_j^{\mathrm{SMEFT}} = \boxed{\frac{S_i}{(4\pi f)^2}}$$



$t\bar{t}$ data

$m_{t\bar{t}}$

$\sqrt{s}$	Collab.	Channel	bins	Ref.
8 TeV	ATLAS	Dilepton	6	[82]
8 TeV	ATLAS	ℓ+jets	7	[83]
8 TeV	CMS	Dilepton	6	[84](a)
8 TeV	CMS	ℓ+jets	7	[84](b)
13 TeV	ATLAS	ℓ+jets	9	[85]
13 TeV	CMS	Dilepton	7	[86]
13 TeV	CMS	ℓ+jets	10	[87]
13 TeV	CMS	ℓ+jets	15	[88]

p_T

$\sqrt{s}$	Collab.	channel	bins	Ref.
8 TeV	ATLAS	ℓ+jets	8	[83]
8 TeV	CMS	Dilepton	5	[84](a)
8 TeV	CMS	ℓ+jets	8	[84](b)
13 TeV	ATLAS	ℓ+jets	8	[85]
13 TeV	CMS	Dilepton	6	[86]
13 TeV	CMS	ℓ+jets	17	[88]

[82] ATLAS collaboration, *Measurement of top quark pair differential cross-sections in the dilepton channel in pp collisions at $\sqrt{s} = 7$ and 8 TeV with ATLAS*, Phys. Rev. D **94** (2016) 092003 [*Addendum ibid.* **101** (2020) 119901] [arXiv:1607.07281] [INSPIRE].

[83] ATLAS collaboration, *Measurements of top-quark pair differential cross-sections in the lepton+jets channel in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector*, Eur. Phys. J. C **76** (2016) 538 [arXiv:1511.04716] [INSPIRE].

[84] CMS collaboration, *Measurement of the differential cross section for top quark pair production in pp collisions at $\sqrt{s} = 8$ TeV*, Eur. Phys. J. C **75** (2015) 542 [arXiv:1505.04480] [INSPIRE].

[85] ATLAS collaboration, *Measurements of top-quark pair differential and double-differential cross-sections in the ℓ+jets channel with pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector*, Eur. Phys. J. C **79** (2019) 1028 [*Erratum ibid.* **80** (2020) 1092] [arXiv:1908.07305] [INSPIRE].

[86] CMS collaboration, *Measurements of $t\bar{t}$ differential cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV using events containing two leptons*, JHEP **02** (2019) 149 [arXiv:1811.06625] [INSPIRE].

[87] CMS collaboration, *Measurement of differential cross sections for the production of top quark pairs and of additional jets in lepton+jets events from pp collisions at $\sqrt{s} = 13$ TeV*, Phys. Rev. D **97** (2018) 112003 [arXiv:1803.08856] [INSPIRE].

[88] CMS collaboration, *Measurement of differential $t\bar{t}$ production cross sections in the full kinematic range using lepton+jets events from proton-proton collisions at $\sqrt{s} = 13$ TeV*, Phys. Rev. D **104** (2021) 092013 [arXiv:2108.02803] [INSPIRE].

Chose independent combination to maximise sensitivity

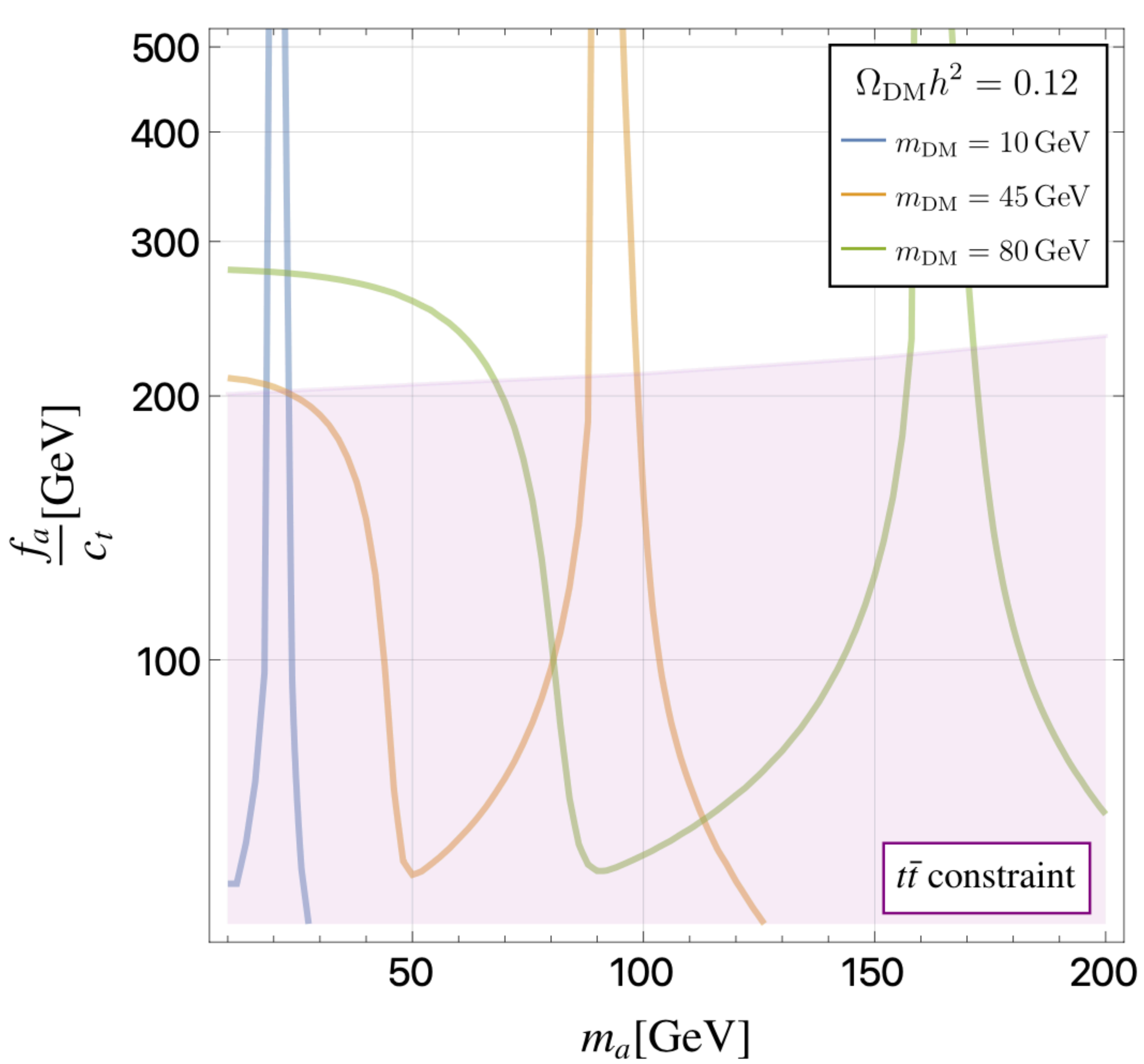
DM mediator

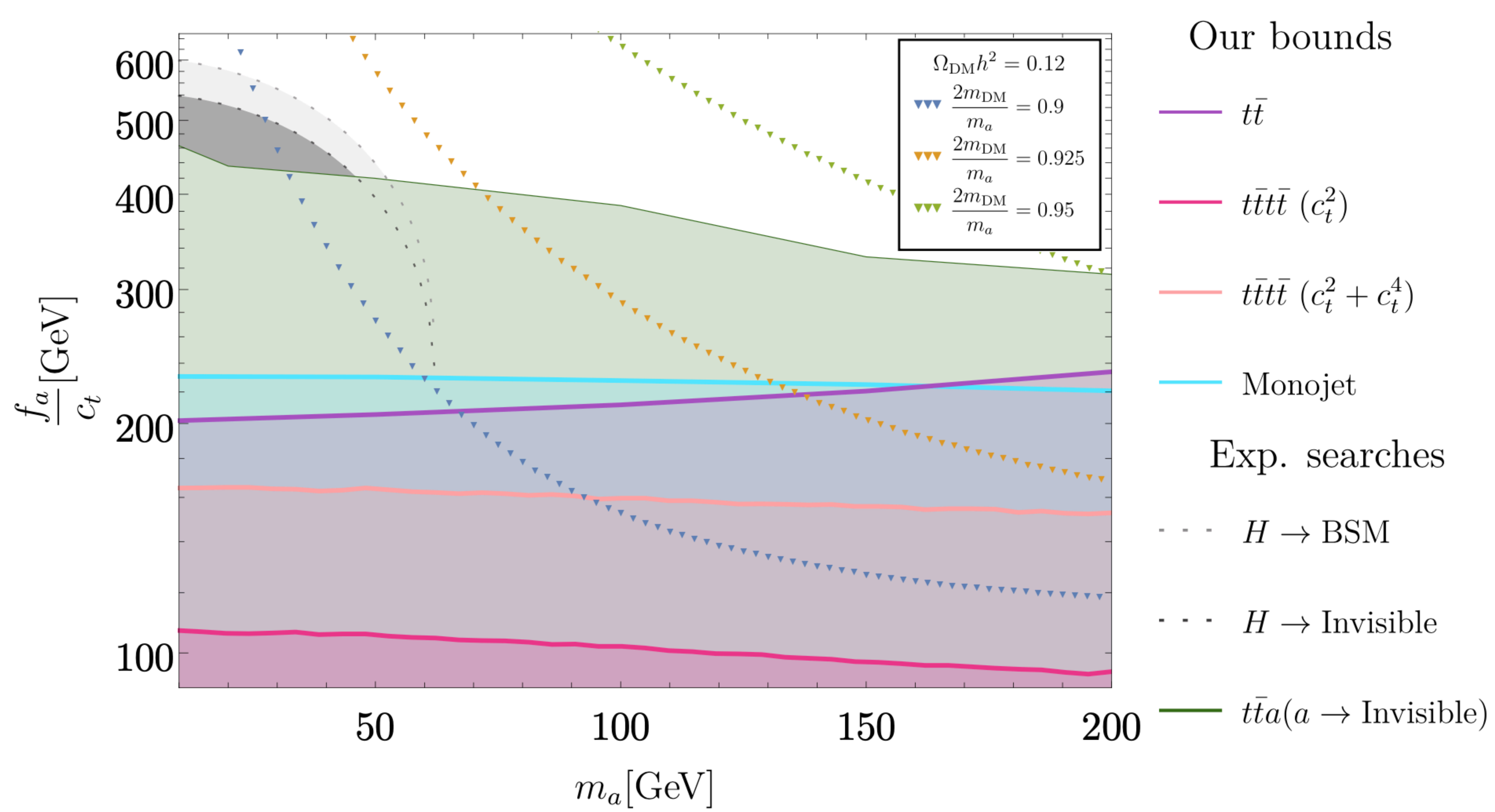
$$\mathscr{L}_{\text{ALP}} \supset i\bar{\chi}\partial^{\mu}\gamma_{\mu}\chi - m_{\text{DM}} - ic_{\text{DM}}\frac{m_{\text{DM}}}{f_a}a\bar{\chi}\gamma^5\chi$$

Indirect searches constrain DM mediator scenario

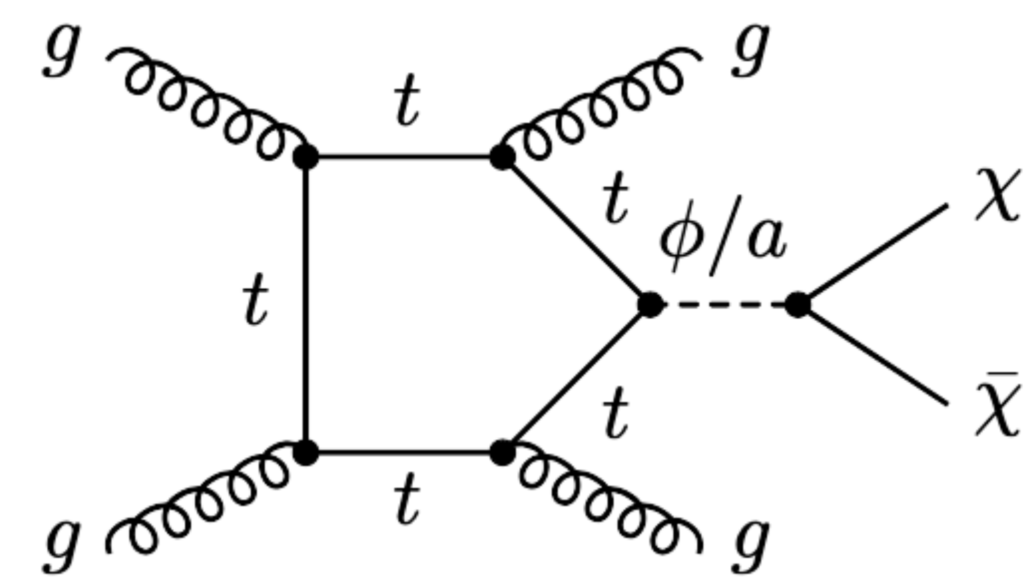
Dedicated missing E_T searches are more powerful

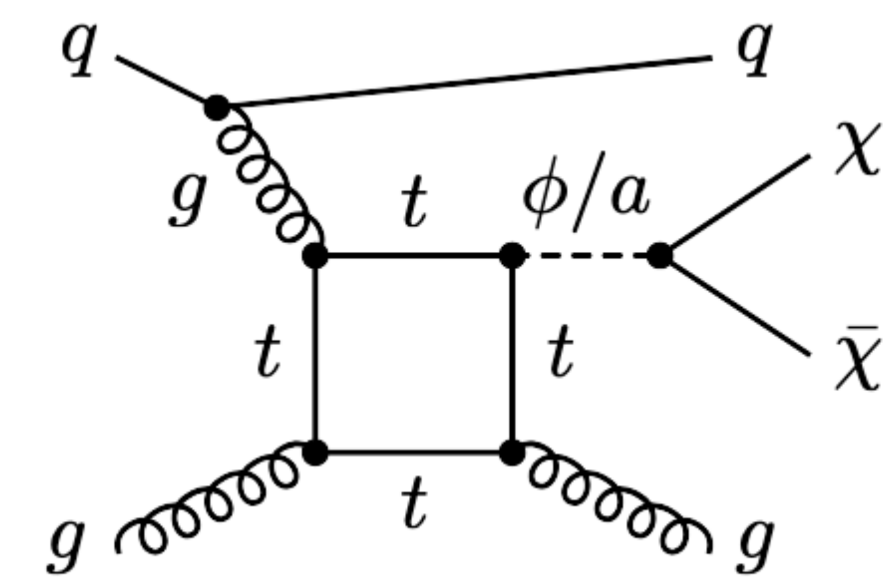
- $h \to$ invisible, $t\bar{t}(a \to \mathbf{MET})$ & monojet





$pp \to ajj$

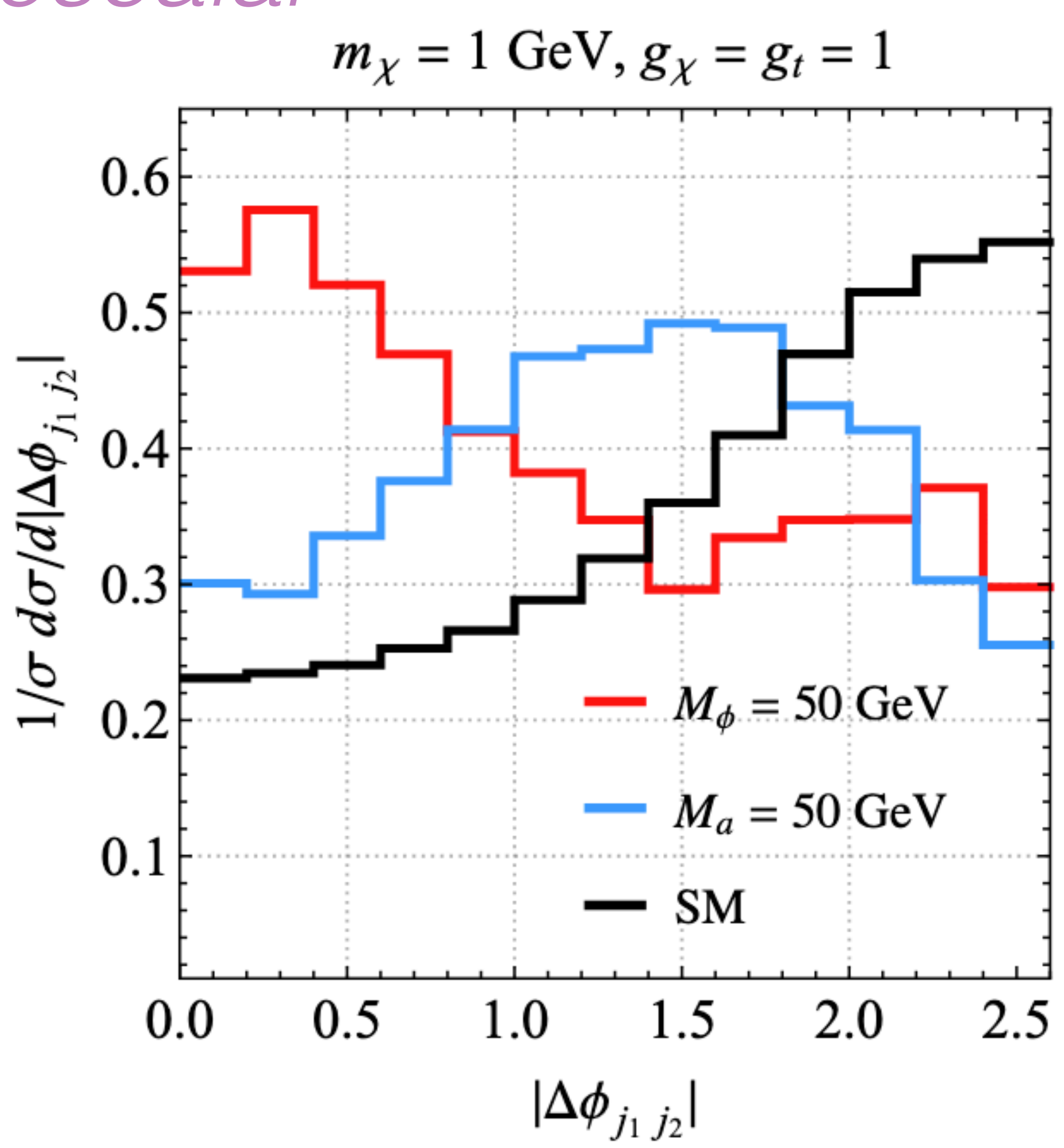


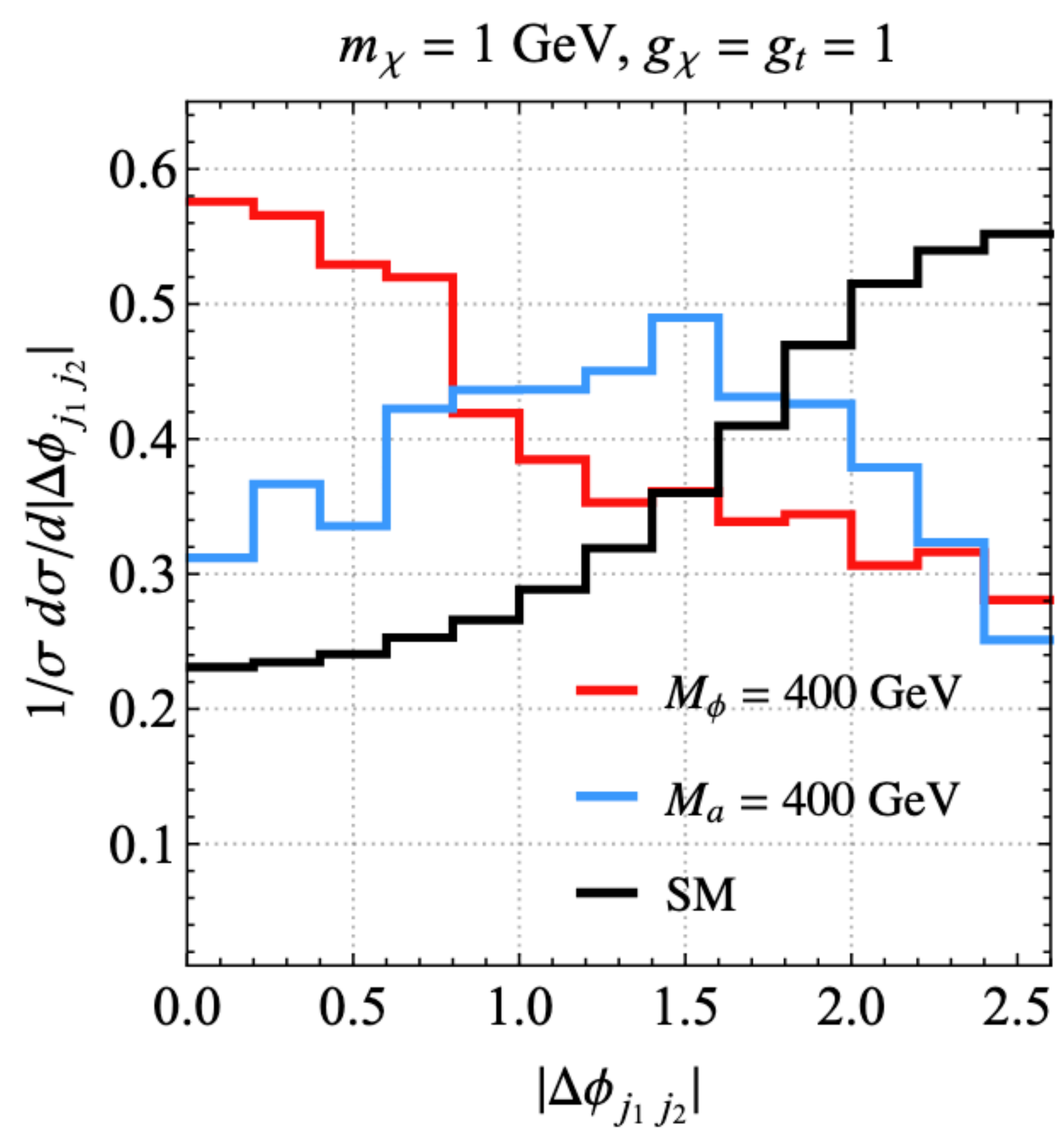


It is known that this channel probes CP of scalar

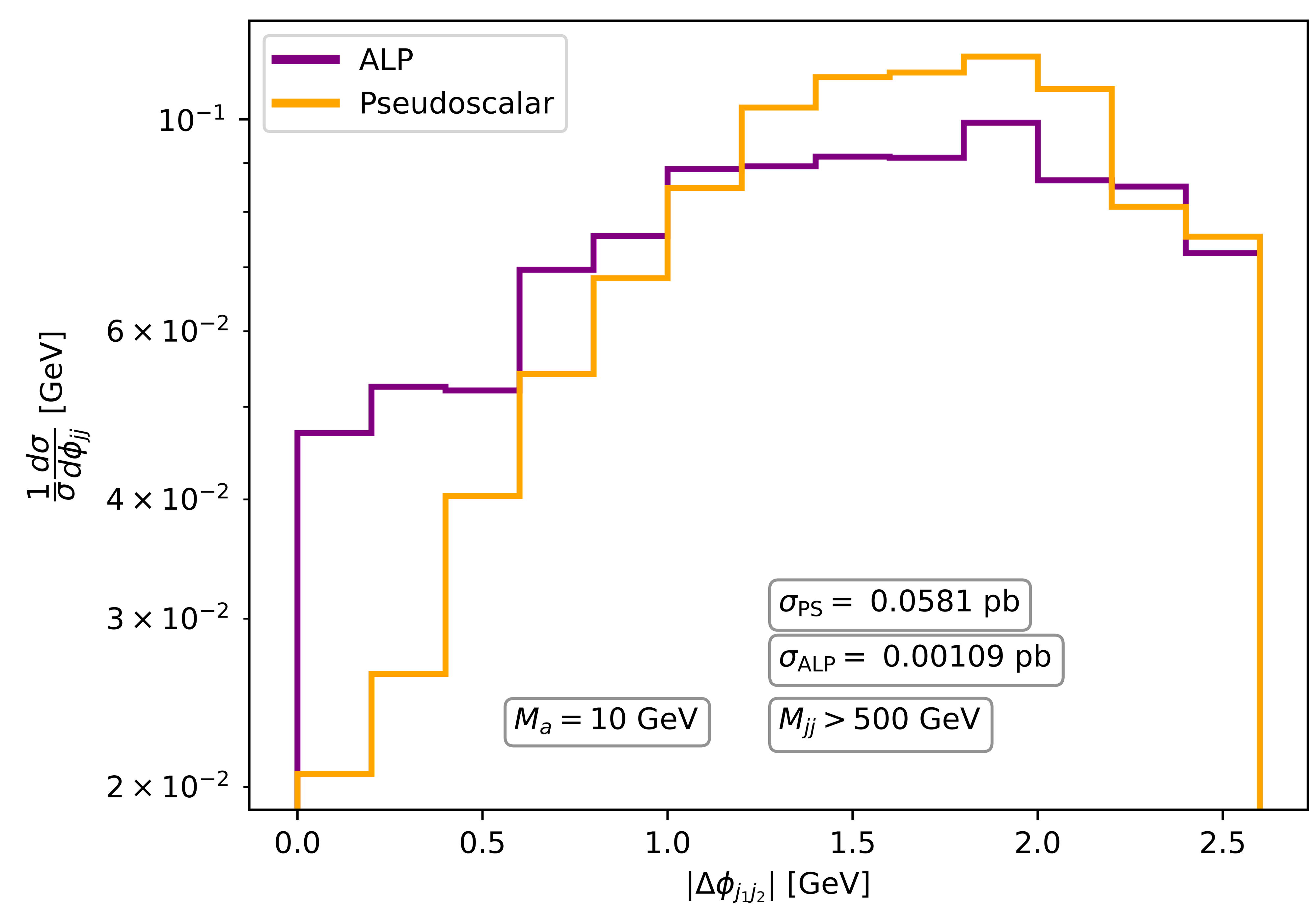
- Dijet + MET as a probe for (pseudo)scalar DM mediator

Scalar vs. pseudoscalar [Haisch & Polesello; JHEP 02 (2019)128]



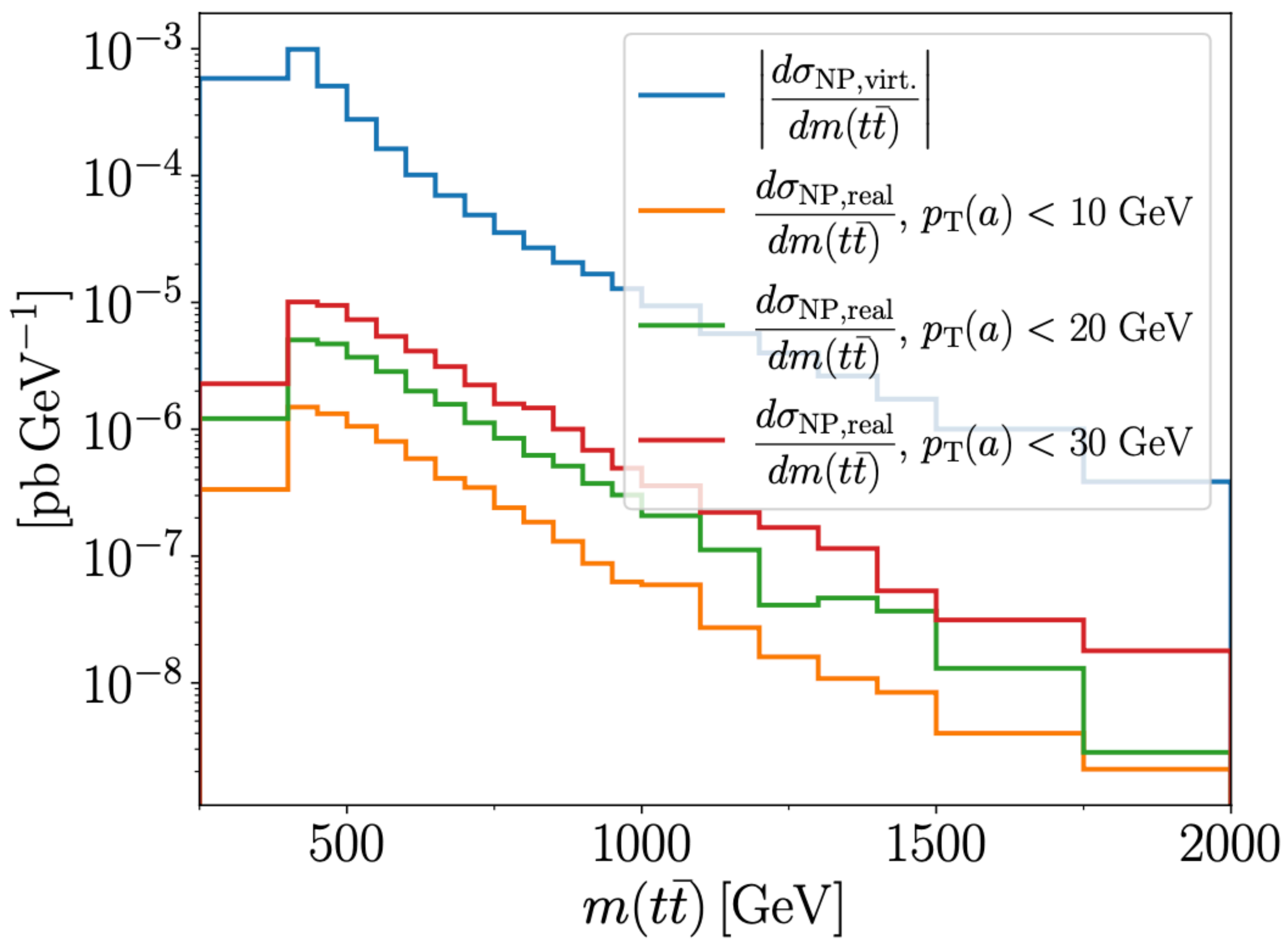


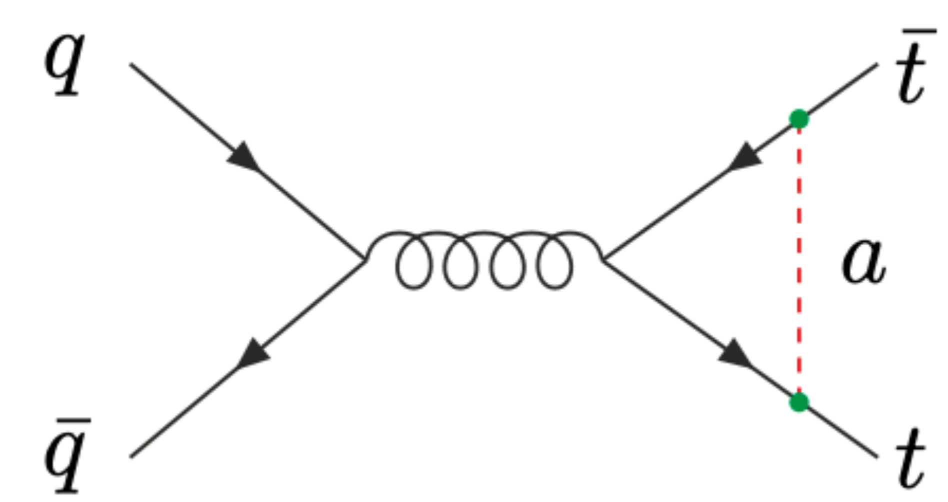
pseudoscalar vs ALP

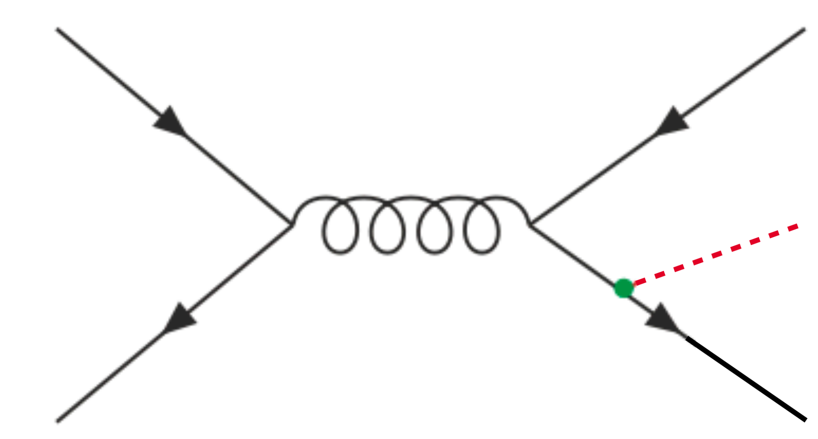


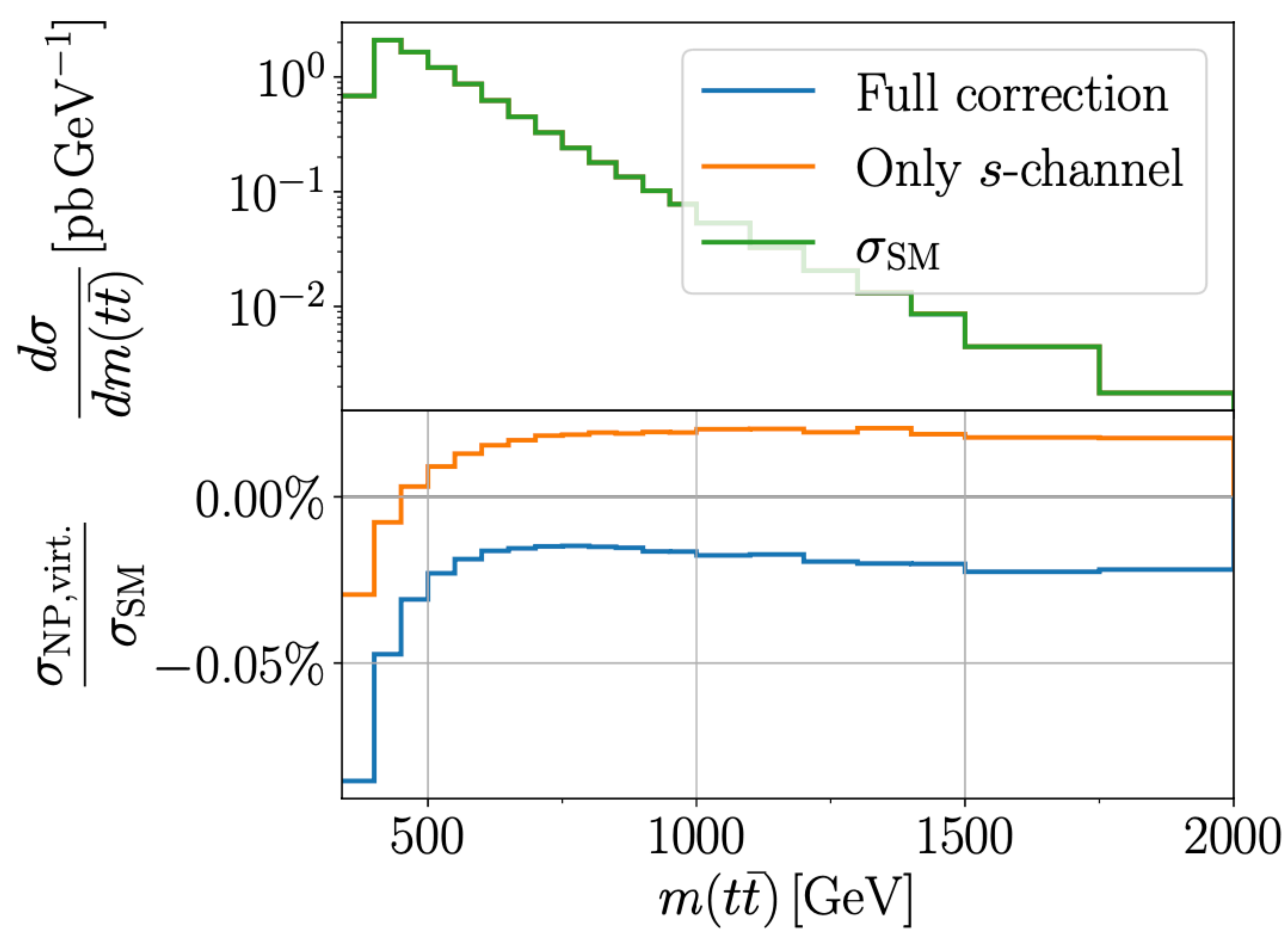
- ALP differs from pseudo scalar
- Very small production cross-section…

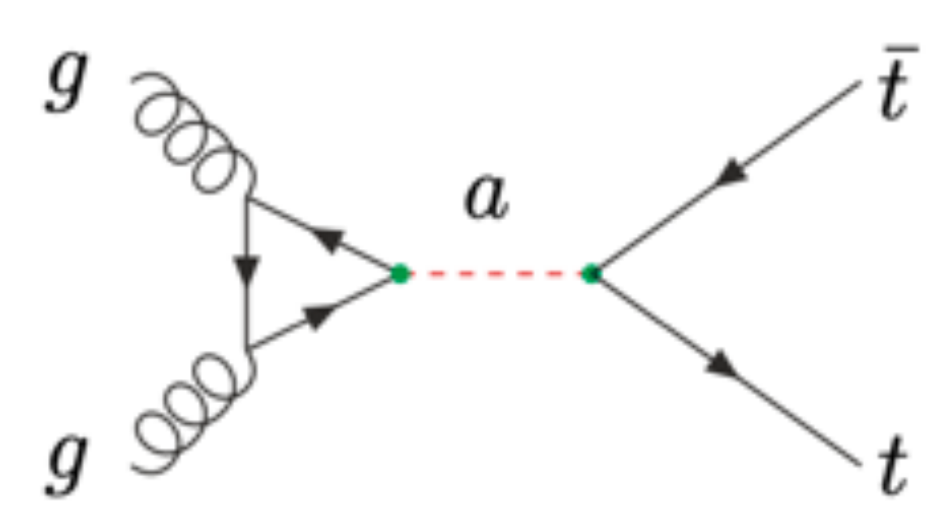
Real vs. virt. & s-channel

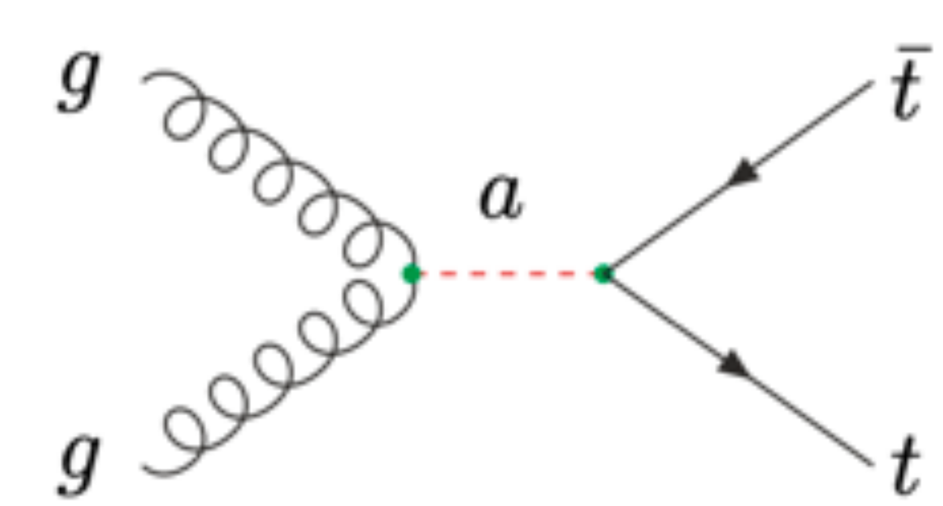












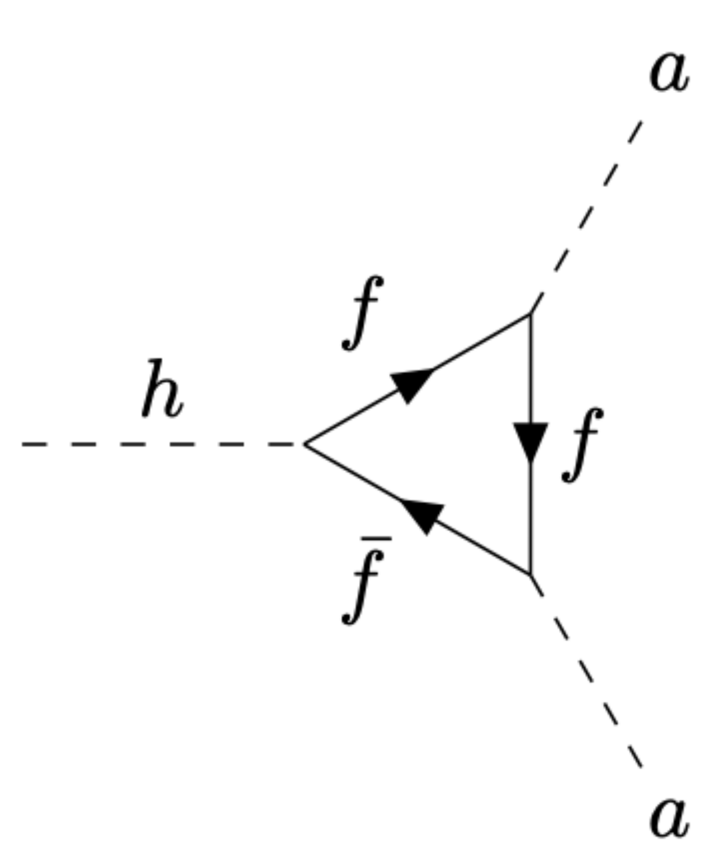
Assumptions & caveats

Only c_t is generated at matching scale, Λ

- Some couplings generated by RG running assumed to be zero at Λ
- We set Λ=1 TeV, $c_i \propto \log \frac{\Lambda}{E}$

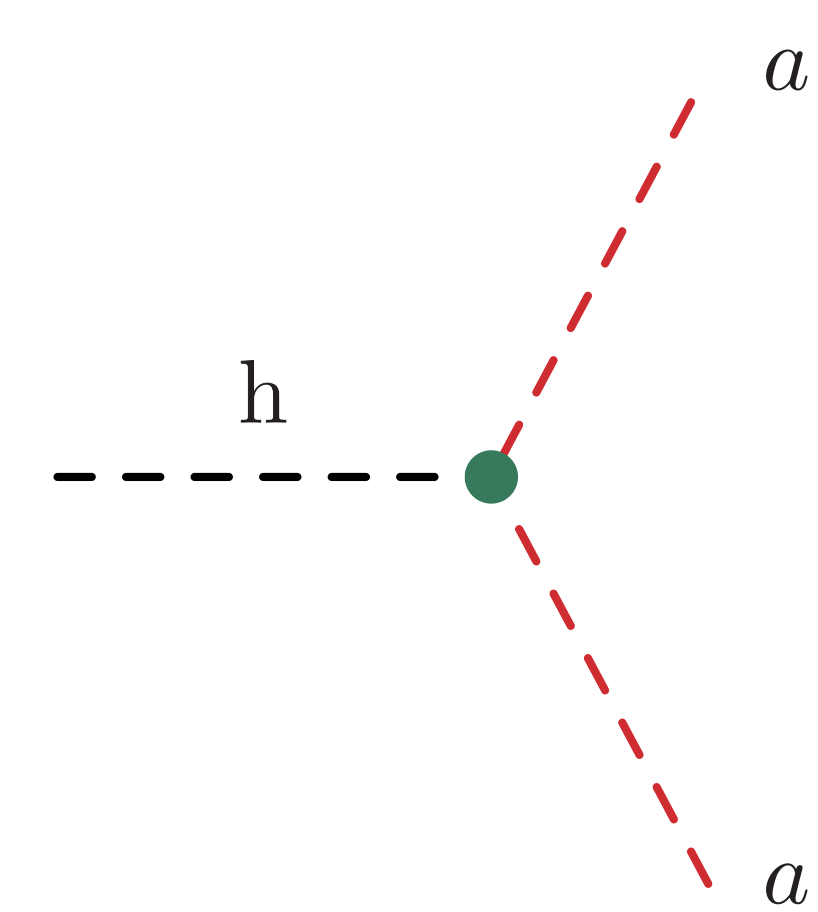
Indirect bounds arise at order $1/f_a^2 \Rightarrow$ dimension-6

- ALP-EFT & SMEFT operators at dim-6 also assumed to be zero at Λ
- e.g. $h \to aa$ can also arise at tree level @ dim-6 from $c_{aH}^{(6)}$



$\propto \frac{c_f^2}{f_a^2}$

$\frac{c_{aH}^{(6)}}{f_a^2}(\phi^\dagger\phi)\,\partial^\mu a \partial_\mu a \quad \Rightarrow$



Toy model

SM + 2 vector-like fermions: T, Ψ & complex scalar, Φ

- T, Ψ share top quantum numbers (top partners)

$$\mathcal{L}_{\rm UV} = y\Phi\bar{T}_L T_R + \delta\bar{T}_L t_R + y'\Phi^*\bar{\Psi}_L\Psi_R + \delta'\bar{\Psi}_L t_R + \text{h.c.}\,,$$

- Chirally charged under a global $U(1)$ symmetry, broken by $\langle\Phi\rangle = f_a$

$$Q(\Phi) = 1, \quad Q(T_R) = -1, \quad Q(\Psi_R) = 1\,; \qquad \Phi = \frac{1}{\sqrt{2}}(f_a + \rho)e^{ia/f_a}$$

$$T_R \to e^{-ia/f_a} T_R \qquad \Psi_R \to e^{ia/f_a}\Psi_R$$

$$\Rightarrow \quad \mathcal{L}_{\rm UV} = -\frac{1}{f_a}\partial_\mu a\bar{T}_R\gamma^\mu T_R + \frac{1}{f_a}\partial_\mu a\bar{\Psi}_R\gamma^\mu\Psi_R - m_T\bar{T}T - m_\Psi\bar{\Psi}\Psi + \left(\delta\bar{T}_L t_R + \text{h.c.}\right)$$

- One massless combination before EWSB: $c_\theta t_R + s_\theta T_R$
- Integrating out T_R leads to our ALP-top interaction, $c_t = -\,\delta^2/m_T^2$

$$\frac{\delta\mathcal{L}_{\rm UV}}{\delta\bar{T}_L} = \frac{\delta\mathcal{L}_{\rm UV}}{\delta\bar{T}_R} = 0 \quad \to \quad T_R = \frac{\delta}{m_T}t_R\,, \quad T_L = -\frac{\delta}{m_T^2 f_a}\partial_\mu a\gamma^\mu t_R\,. \qquad \Rightarrow \qquad \mathcal{L}_{a,\rm int} = -\frac{\delta^2}{m_T^2}\frac{1}{f_a}(\partial_\mu a)\,\bar{t}_R\gamma^\mu t_R$$

Toy model 2

Dimension-6 operator, $\mathcal{O}_{aH}^{(6)}$ depends on Φ potential

$$\mathscr{L}_\Phi = |\partial_\mu \Phi|^2 + \mu^2 |\Phi|^2 - \lambda |\Phi|^4 + \boxed{\kappa |\Phi|^2 \phi^\dagger \phi}$$ Higgs portal

After $U(1)$ symmetry breaking $\quad \Phi = \frac{1}{\sqrt{2}}(f_a + \rho) e^{ia/f_a}$

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \rho)^2 + \frac{1}{2}(\partial_\mu a)^2 + \frac{\rho}{f_a}(\partial_\mu a)^2 - \frac{1}{2} m_\rho^2 \rho^2 + \frac{\kappa}{2}(f_a^2 + 2\rho f_a + \rho^2)\phi^\dagger \phi + \mathcal{O}(\rho^3) \qquad (m_\rho^2 = \lambda f_a^2)$$

Integrate out ρ at tree level yields dimension-6 operator

$$\frac{\kappa}{\lambda} \frac{1}{f_a^2} (\phi^\dagger \phi)\, \partial^\mu a \partial_\mu a$$

Depends on $|\Phi|^2 |\phi|^2$ portal relative to $|\Phi|^4$ interaction

UV interpretation

SMEFT-UV connection is model dependent by construction

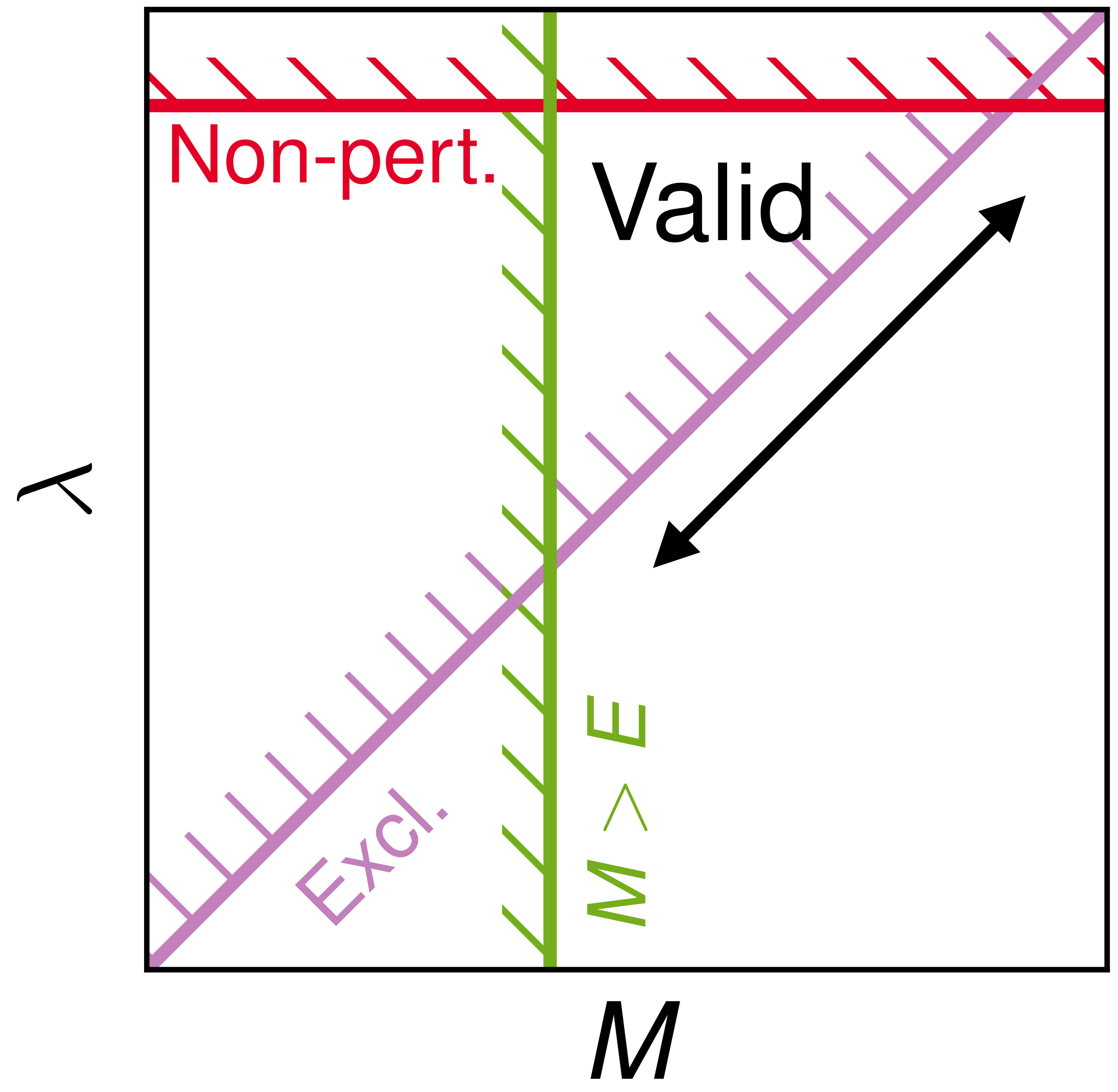
- Implications on heavy new physics & validity of EFT is ***a posteriori***
- Depends on sensitivity & energy scale probed by data
- Bottom-up philosophy: new physics scale unknown

arbitrary dimensionful parameter

$$\frac{c}{f_a} = \frac{\lambda}{M}$$

coupling/mass scale of new physics

constraint: c/f_a < X



In general:

- Larger coupling ⇔ higher new physics scale
- Better for EFT validity
- Some coefficients typically come with loop factors
- e.g. c_{VV} gauge interactions